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Documentation of National Weather Conditions Affecting Long-Term Degradation of Commercial Spent Nuclear Fuel and DOE Spent Nuclear Fuel and High-Level Waste

Prepared for

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of the Yucca Mountain
Environmental Impact Statement

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Documentation of National Weather Conditions Affecting Long-Term Degradation of Commercial Spent Nuclear Fuel and DOE Spent Nuclear Fuel and High-Level Waste

1.0 Introduction

The U.S. Department of Energy (DOE) is preparing a proposal to construct, operate and monitor, and eventually close a repository at Yucca Mountain in Nye County, Nevada, for the geologic disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW). As part of this effort, DOE has prepared a viability assessment and an assessment of potential consequences that may exist if the repository is not constructed. The assessment of potential consequences if the repository is not constructed assumes that all SNF and HLW would be left at the generator sites. These include 72 commercial generator sites (three commercial facility pairs -- Salem and Hope Creek, Fitzpatrick and Nine Mile Point, and Dresden and Morris -- would share common storage due to their close proximity to each other) and five DOE sites across the country. DOE analyzed the environmental consequences of the effects of the continued storage of these materials at these sites in a report titled *Continued Storage Analysis Report* (CSAR; Reference 1). The CSAR analysis includes a discussion of the degradation of these materials when exposed to the environment.

This document describes the environmental parameters that influence the degradation analyzed in the CSAR. These include temperature, relative humidity, precipitation chemistry (pH and chemical composition), annual precipitation rates, annual number of rain-days, and annual freeze/thaw cycles. The document also tabulates weather conditions for each storage site, evaluates the degradation of concrete storage modules and vaults in different regions of the country, and provides a thermal analysis of commercial SNF in storage.

2.0 Concrete Storage Module Degradation

Reference 2 developed and documented the degradation mechanisms related to failure of the concrete storage module (CSM). The analysis considered degradation due to exposure to the surrounding environment. In that reference, *Failure* is defined as the time when precipitation would infiltrate the concrete and reach the SNF or HLW storage canister. The primary cause of failure of surface-mounted concrete structures would be freeze/thaw cycles that caused the concrete to crack and spall (break off in layers), which would allow precipitation to enter the concrete, causing more freeze damage. *Freeze/thaw failure* (Reference 2) is defined as the time when half of the thickness of the concrete had been cracked and spalled. The freeze-thaw process is discussed in Reference 2. Some regions (e.g., coastal California, Texas, and Florida) essentially would be unaffected by freeze/thaw damage. In these locations the primary failure mechanism would be chlorides in precipitation, which would decompose the chemical constituents of the concrete into sand-like materials. This process would progress more slowly than the freeze/thaw process and is also discussed in Reference 2.

The calculated time for onset of damage and roof collapse at nuclear storage sites are shown on Table 2-1. The analysis includes damage from freeze/thaw and chemical attack. The first three sites (Vogtle, Perry, and Monticello) identified in Table 2-1 were representative of most storage sites in the United States where freezes are experienced. The remaining sites, shown in the table, are those sites with very limited freezing weather. The main cause of damage is from the effects of the freeze/thaw process at the sites. The analysis shows that chemical attack contributes minimally to failure of the concrete storage modules.

Table 2-1. Example information for concrete freeze/thaw (times are from loss of institutional control).

1	2	3	4	5	6	7	8	9	10	11	12	13
Location of Weathering	Augusta, GA	Cleveland, OH	Saint Cloud, MN	Sacramento, CA	Santa Maria, CA	Eureka, CA	Victoria, TX	Tampa, FL	Phoenix, AZ	West Palm Beach, FL	Miami, FL	San Diego & Los Angeles, CA
Reactor	Vogtle	Perry	Monticello	Rancho Seco	Diablo Canyon	Humboldt Bay	South Texas	Crystal River	Palo Verde	St. Lucie	Turkey Point	San Onofre
Precipitation (inches) during months with temperature falling below freezing	25	22.6	15.8	14.4	11.97	28.53	10.2	12	3.9	11.6	3.8	No Prec with freezing
Freezing (days/year)	56.2	125.5	176.9	17.4	20.1	5	12.2	3.6	7.7	0.8	0.2	no freezing
Weathering Index (day-inches)	1,405	2,832	2,788	251	241	143	124	43	30	9	1	infinity
Time to Onset of damage (penetration reached 3"), yrs.	18	9	9	100	104	175	200	580	835	2,680	32,500	infinity
Time to Roof Collapse, yrs. (Freeze/thaw failure only)	160	79	81	898	935	1,577	1,800	5,200	7,510	24,200	293,000	infinity
Time to Roof Collapse, yrs. (All failure modes combined)	159	78.7	80.5	832	870	1,380	1,550	3,550	4,500	7,600	10,700	11,000
% Failure contributed by Freeze/thaw degradiation	99.4	99.6	99.4	92.6	93.0	87.5	86.1	68.3	59.9	31.4	3.7	0.0

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In fact when no freeze/thaw damage occurs to the concrete storage modules, the concrete could be expected to last 11,000 years.

As described in the summary of Reference 2, "Underground concrete structures are expected to last longer because they are in a more benign environment. For example, the Glass Waste Storage Facility at Savannah River Site (SRS) near Augusta, GA was evaluated, and the concrete within it was found to last about 3,000 years. However, the expected failure sequence for that facility may not be concrete failure. The weather protection portion of that facility (i.e., the roof) should protect its contents for 150 years until that cover is lost. At that time, the contents of the vault (in this case the High-Level Waste as a borosilicate glass in a stainless steel canister) will be exposed to precipitation. From 150 to 3,000 years the concrete vault is expected to serve as a tub, and the engineered barrier of the canister and leach resistance of the glass must provide protection. (The protection provided by the waste canister and the waste itself were not evaluated in Reference 2.)

Since the chemical degradation of underground facilities has been previously identified in Reference 2, that analyses is summarized in Section 2.2.1 of this report. Section 2.2.2 has five subparts and describes chemical degradation for surface facilities and determine the rate of degradation.

The following sections discuss in more detail the freeze-thaw and chemical attack processes, describe the input data and sources used, and present results of the analysis. Section 2.1 discusses concrete degradation by freeze-thaw phenomenon. Concrete degradation by chemical attack (sulfate attack, magnesium attack, calcium leaching, carbonation, chloride penetration, and rebar corrosion, is discussed in Section 2.2. Sections 3.0 through 5.0 provide the source and use of precipitation data, precipitation chemistry (concentrations of chemicals in rainfall), and relative humidity data, respectively. Section 6.0 discusses degradation of engineered barriers (concrete casks and stainless steel containers) as affected by the temperature conditions at the nuclear reactor sites.

2.1 Concrete Degradation from Freeze/Thaw

Concrete degradation due to freeze/thaw depends on the number of days the temperature is below freezing and the amount of precipitation on these days. Table 2-2 shows the number of days in each month with temperature below freezing and the amount of precipitation that occurred during these months. This information was obtained from Local Climatological Data assembled by the National Climatic Data Center in Asheville, NC (Reference 3) using a minimum of 30 years of data. For each site where SNF currently is stored and for all of the DOE site storing DOE-SNF and DOE-HWL, the weathering index (day-inches) was calculated by multiplying the number of freezing days times the winter precipitation expressed in inches. As described in Reference 2, the assumed freeze/thaw damage uses this weathering index. The weathering index also is provided in Table 2-2 for each site. Reference 2 defines the following concrete failure stages:

- *Onset of damage* is defined as penetration of the outer concrete surface to a depth 3 inches.

- *Complete failure* is defined as penetration of concrete to depth 50 percent of its thickness, which is assumed to be loss of weather protection afforded by the concrete.

The calculated time for onset of damage and roof collapse (years of weather protection) are shown on Table 2-2. If several cities are located near a single site, and no meteorological station was available near the site with long-term weather data, the site data were estimated from the average data of the several cities surrounding the site.

Table 2-2. Commercial reactor freeze/thaw data (1 of 13).

Reactor site number	1	2	3			4			5	6
Record (years)	30	30	30	30	30	30	30	30		30
	Vogle	Perry	Montecello	VC Summer	VC Summer	VC Summer	San Onofre	San Onofre	San Onofre	St Lucie
Freezing (days/month)	Augusta, GA	Cleveland Ohio	Saint Cloud Michigan	Columbia South Carolina	Greenville South Carolina	Average	San Diego, California	Los Angeles California	Average	West Palm Beach Florida
June										
July										
August										
September			1.8							
October	0.8	2.8	13	1.2	0.9	1.05				
November	6.7	12.5	26.2	7.5	6.6	7.05				
December	14.2	24.8	30.6	14.7	15.4	15.05				0.2
January	16.7	27.9	31	17.3	19	18.15				0.4
February	12.5	24.3	27.6	13.1	15.3	14.2				0.1
March	4.7	21	27.7	5.8	7.2	6.5				0.1
April	0.6	9.3	15.9	0.9	1	0.95				
May		0.9	3.1							
Total	56.2	125.5	176.9	60.5	65.4	62.95	0	0	0	0.8
Precipitation										
June										
July										
August										
September			3.16							
October	2.84	2.54	2.21	3.04	3.99	3.515	0.37	0.34		
November	2.48	3.17	1.27	2.9	3.65	3.275	1.45	1.75		
December	3.4	3.09	0.83	3.59	4.14	3.865	1.57	1.66		2.49
January	4.05	2.04	0.74	4.42	4.1	4.26	1.8	2.4		2.8
February	4.27	2.19	0.63	4.12	4.41	4.265	1.53	2.51		2.69
March	4.65	2.91	1.41	4.82	5.39	5.105	1.77	1.98		3.66
April	3.31	3.14	2.35	3.28	3.86	3.57	0.79	0.72		
May		3.49	3.16							
Total Winter Precip.	25	22.57	15.76	26.17	29.54	27.855	9.28	11.36	10.32	11.64
Total - end Mo	18.85			22.89	25.68	24.285				
Unadjusted Weathering Index, day-inches	1,405	2,833	2,788	1,583	1,932	1,757.6005	0			9
Onset of Damage, yr	17.8	8.8	9.0			14.2				2,684.7
Roof Collapse Years	160	79	81			128				

Table 2-2. Commercial reactor freeze/thaw data (2 of 13).

Reactor site number	7	8	9			10	11, 12, & 13
Record (years)	30	30	30	30			30
	Maine Yankee	Palo Verde	Three Mi Island	Arkansas Nuc #1	Arkansas Nuc #1	Arkansas Nuc #1	Dresden La Salle Braidwood
	Portland, Me	Phoenix Arizona	Middletown Pennsylvania	Fort Smith Arkansas	Little Rock Arkansas	Average	Peoria Illinois
Freezing (days/month)							
June							
July							
August							
September	0.8						0.1
October	8.6		1.8	0.7	0.2	0.45	4.7
November	19.3	0.2	8.8	8.3	5.3	6.8	16.7
December	28.9	2	24.2	20.1	15.6	17.85	26.7
January	29.9	3.7	27.7	24	20.5	22.25	29.4
February	26.5	1.4	23.8	16.8	13.7	15.25	25.3
March	25.2	0.4	14	7.5	4.5	6	19.5
April	13.5		3.4	1	0.5	0.75	5.9
May	2						0.4
Total	154.7	7.7	103.7	78.4	60.3	69.35	128.7
Precipitation							
June							
July							
August							
September	3.09						3.87
October	3.9		2.93	3.68	3.75	3.715	2.65
November	5.17	0.66	3.52	3.99	5.2	4.595	2.69
December	4.55	1	3.24	3.03	4.83	3.93	2.44
January	3.53	0.67	2.84	1.9	3.42	2.66	1.51
February	3.33	0.68	2.93	2.6	3.61	3.105	1.42
March	3.67	0.88	3.28	3.95	4.91	4.43	2.91
April	4.08		3.24	3.97	5.46	4.715	3.77
May	3.63						3.7
Total Winter Precip.	34.95	3.89	21.98	23.12	31.18	27.15	24.96
Total - end Mo							
Unadjusted Weathering Index, day-inches	5,407	30	2,279	1,813	1,880	1,846	3,212
Onset of Damage, yr	4.6	834.6	11.0	13.8	13.3	13.5	7.8
Roof Collapse Years	42	~~7,512~~	99	124	120	122	70

Table 2-2. Commercial reactor freeze/thaw data (3 of 13).

Reactor site number	14			15	16			17	18	19, 20
Record (years)	30 Clinton	Clinton	Clinton	30 Byron	30 Duane Arnold	30 Duane Arnold	Duane Arnold	30 Yankee Rowe	30 Rancho Seco	30 Catawba Mc Guire
Freezing (days/month)	Peoria Illinois	Springfield Illinois	Average	Rockford, IL	Des Moines, Iowa	Peoria Illinois	Average	Albany New York	Sacramento California	Charlotte North Carolina
June										
July										
August										
September	0.1		0.05	0.4	0.2	0.1	0.15	0.7		
October	4.7	3.6	4.15	6.8	4.7	4.7	4.7	8.4		0.8
November	16.7	14.5	15.6	19.3	18.6	16.7	17.65	18.1	1.2	6.6
December	26.7	25.3	26	28	28.9	26.7	27.8	27.7	6.9	15.9
January	29.4	28.1	28.75	29.6	30	29.4	29.7	29.6	7	19.2
February	25.3	23.6	24.45	26.2	25.6	25.3	25.45	25.9	1.8	15.6
March	19.5	17.1	18.3	23.2	20.7	19.5	20.1	24.4	0.5	7.5
April	5.9	4.3	5.1	9.3	6.6	5.9	6.25	12.5		1.1
May	0.4	0.2	0.3	1.3	0.2	0.4	0.3	1.7		
Total	128.7	116.7	122.7	144.1	135.5	128.7	132.1	149	17.4	66.7
Precipitation										
June										
July										
August										
September	3.87		1.935	2.88	3.53	3.87	3.7	2.95		
October	2.65	2.6	2.625	2.57	2.62	2.65	2.635	2.83		3.5
November	2.69	2.53	2.61	2.05	1.79	2.69	2.24	3.23	2.72	3.36
December	2.44	2.73	2.585	1.28	1.32	2.44	1.88	2.93	2.51	3.23
January	1.51	1.51	1.51	1.14	0.96	1.51	1.235	2.36	3.73	3.48
February	1.42	1.77	1.595	2.46	1.11	1.42	1.265	2.27	2.87	3.71
March	2.91	3.24	3.075	3.65	2.33	2.91	2.62	2.93	2.57	3.84
April	3.77	3.68	3.725	3.66	3.36	3.77	3.565	2.99		4.43
May	3.7	3.62	3.66		3.66	3.7	3.68	3.41		
Total Winter Precip.	24.96	21.68	23.32	19.69	20.68	24.96	22.82	25.9	14.4	25.55
Total - end Mo										
Unadjusted Weathering Index, day-inches	3,212	2,530	2,871.20	2,837	2,802	3,212	3,007.246	3,859	251	1,704
Onset of Damage, yr			8.7	8.8			8.3	6.5	99.8	14.7
Roof Collapse Years			78	79			75	58	898	132

Table 2-2. Commercial reactor freeze/thaw data (4 of 13).

Reactor site number	21	22, 23			24	25	26			27
Record (years)	30 Pilgrim	30 Millstone Haddam Neck	30 Grand Gulf	29 Grand Gulf SAR info	Grand Gulf	30 River Bend	30 Sequoyah	30 Watts Bar	30 Watts Bar	Watts Bar
Freezing (days/month)	Boston Massachusetts	Bridgeport Connecticut	Jackson Mississippi	Vicksburg Mississippi	Average	Baton Rouge Louisiana	Chattanooga Tennessee	Chattanooga Tennessee	Knoxville Tennessee	Average
June										
July										
August										
September	0.6									
October	7	1	0.5		0.25		1.1	1.1	1	1.05
November	22.3	7.2	5.7	2	3.85	1.6	8.6	8.6	7.6	8.1
December	26.1	21.7	12.6	6	9.3	6.4	17.7	17.7	17.7	17.7
January	23.5	26.4	15.3	9	12.15	9.3	20.9	20.9	20.8	20.85
February	16.8	23.6	11.3	5	8.15	5.1	16	16	16.5	16.25
March	2.7	17.1	4.2	1	2.6	1.1	8.1	8.1	8.6	8.35
April		3.6	0.4		0.2		1.7	1.7	1.8	1.75
May		0.1								
Total	99	100.7	50	23	36.5	23.5	74.1	74.1	74	74.05
Precipitation										
June										
July										
August										
September										
October	3.3	3.11	3.26		1.63		3.22	3.22	2.84	3.03
November	4.22	3.81	4.81	4.43	4.62	4.31	4.61	4.61	3.75	4.18
December	4.01	3.5	5.91	4.94	5.425	5.53	5.17	5.17	4.54	4.855
January	3.59	3.24	5.24	5.13	5.185	4.91	4.89	4.89	4.17	4.53
February	3.62	3.01	4.7	5.31	5.005	5.52	4.81	4.81	4.06	4.435
March	3.69	3.75	5.82	5.73	5.775	4.81	6.03	6.03	5.09	5.56
April	3.6	3.76	5.57		2.785		4.31	4.31	3.72	4.015
May		3.93								
Total Winter Precip.	26.03	28.11	35.31	25.54	30.425	25.08	33.04	33.04	28.17	30.61
Total - end Mo										
Unadjusted Weathering Index, day-inches	2,577	2,831	1,766	587	1,176.46	589	2,448	2,448	2,085	2,266
Onset of Damage, yr	9.7	8.8	14.2	42.6	21.3	42.4	10.2			11.0
Roof Collapse Years	87	79	127	383	191	382	92			99

Table 2-2. Commercial reactor freeze/thaw data (5 of 13).

Reactor site number	28			29	30	31	32	33	34
Record (years)	30 Wolf Creek	30 Wolf Creek	Wolf Creek	30 Beaver Valley	30 Crystal River	30 Fermi	30 Trojan	30 Turkey Point	30 Waterford
Freezing (days/month)	Witchita Kansas	Kansas City Missouri	Average	Pittsburg Pennsylvania	Tampa Florida	Detroit Michigan	Portland Oregon	Miami Florida	New Orleans Louisiana
June									
July									
August						0.1			
September						5			
October	1.3	2.2	1.75	4.3		16.4	0.6		
November	14.3	13.5	13.9	14.1	0.1	25.5	4.6		0.8
December	26.8	26.4	26.6	24.5	1	29.2	10.4	0.1	4.7
January	28.4	28.1	28.25	27.3	1.8	25.3	12.4	0.1	6.2
February	22.5	21.9	22.2	23.9	0.6	22.6	7.7		3.5
March	14.6	14.3	14.45	19.5	0.1	10	4.2		0.6
April	2.8	3.8	3.3	8.4		0.9	1.1		
May	0.1	0.1	0.1	0.9			0.1		
Total	110.8	110.3	110.55	122.9	3.6	135	41.1	0.2	15.8
Precipitation									
June									
July									
August									
September						2.87			
October	2.22	3.29	2.755	2.36	1.77	2.1	2.67		
November	1.59	1.92	1.755	2.85	2.15	2.67	5.34		4.42
December	1.2	1.58	1.39	2.92	1.99	2.82	6.13	1.83	5.75
January	0.79	1.09	0.94	2.54	3.08	1.76	5.35	2.01	5.05
February	0.96	1.1	1.03	2.39	3.01	1.74	3.85		6.01
March	2.43	2.51	2.47	3.41		2.55	3.56		4.9
April	2.38	3.12	2.75	3.15		2.95	2.39		
May	3.81	5.04	4.425	3.56		2.92	2.06		
Total Winter Precip.	15.38	19.65	17.52	23.18	12	22.38	31.35	3.84	26.13
Total - end Mo									
Unadjusted Weathering Index, day-inches	1,704	2,167	1,936	2,849	43	3,021	1,288	1	413
Onset of Damage, yr			12.9	8.8	578.7	8.3	19.4	32,552.1	60.6
Roof Collapse Years			116	79		74	175		545

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Table 2-2. Commercial reactor freeze/thaw data (6 of 13).

Reactor site number				35			36	37	38
Record (years)	30 Big Rock Pt	30 Big Rock Pt	30 Big Rock Pt	Big Rock Pt	30 Peach Botm	30 Peach Botm	Peach Botm	30 Indian Point	30 Humbolt Bay
Freezing (days/month)	Alpena Michigan	Sault Ste. Marie Michigan	Muskegon Michigan	Average Michigan	Philadelphia Pennsylvania	Baltimore Maryland	Average	New York New York	Eureka California
June	0.9	0.7		0.53			0		
July				0.00			0		
August		0.1		0.03			0		
September	2.1	2.2	0.3	1.53			0		
October	11.1	11.3	5.3	9.23	1.5	1.9	1.7	0.1	
November	22.7	21.9	15.2	19.93	8.5	10.2	9.35	3.2	0.4
December	29.7	28.9	26.7	28.43	21.2	21.1	21.15	16.3	1.9
January	30.8	30.5	29.2	30.17	26.2	25.3	25.75	22.7	1.6
February	27.7	27.3	26.2	27.07	22.3	21.1	21.7	19.8	0.9
March	29	28.1	23.8	26.97	14	14	14	10.4	0.2
April	20.8	18.7	11.1	16.87	2.6	3.4	3	1.1	
May	7.6	7.5	1.8	5.63			0		
Total	182.4	177.2	139.6	166.4	96.3	97	96.65	73.6	5
Precipitation									
June	3.14	3.04		2.06			0		
July				0.00			0		
August		3.4		1.13			0		
September	3.69	3.11	3.88	3.56			0		
October	3.23	2.1	2.8	2.71	2.62	2.98	2.8	3.02	
November	3.45	2.2	3.15	2.93	3.34	3.32	3.33	3.81	6.44
December	2.88	2.03	3.03	2.65	3.38	3.41	3.395	3.4	6.04
January	2.42	1.64	2.34	2.13	3.21	3.05	3.13	3.04	6
February	1.74	1.29	1.49	1.51	2.79	3.12	2.955	2.86	4.73
March	2.3	2.11	2.51	2.31	3.46	3.38	3.42	3.6	5.32
April	2.35	2.25	2.9	2.50	3.62	3.09	3.355	3.79	
May	2.71	2.74	2.6	2.68			0		
Total Winter Precip.	27.91	25.91	24.7	26.17333333	22.42	22.35	22.385	23.52	28.53
Total - end Mo									
Unadjusted Weathering Index, day-inches	5,091	4,591	3,448	4,355	2,159	2,168	2,164	1,731	143
Onset of Damage, yr				5.7			11.6	14.4	175.3
Roof Collapse Years				52			104	130	

Table 2-2. Commercial reactor freeze/thaw data (7 of 13).

Reactor site number		39		40	41, & 42		43		44
Record (years)	30 Callaway	Callaway	Callaway	30 RE Ginna	30 Salem Hope Creek	30 Hatch	30 Hatch	Hatch	30 Oyster Creek
Freezing (days/month)	Columbia Missouri	Moline Illinois	Average	Rochester New York	Wilmington Delaware	Savannah Georgia	Macon Georgia	Average	Atlantic City New Jersey
June									
July									
August									
September		0.2	0.1	0.1					0.1
October	2.1	5.7	3.9	4.1	1.9	0.1	0.5	0.3	3.4
November	13.6	18.3	15.95	15.1	9.6	2.4	4.7	3.55	12.1
December	25.2	27.3	26.25	26	22.2	8.4	11.4	9.9	22.4
January	27.4	29.5	28.45	28.9	26	10.8	14.5	12.65	25.6
February	21.7	25.2	23.45	25.4	22	7.2	10.1	8.65	21.9
March	14.8	20.6	17.7	23	14.5	1.9	3.7	2.8	16.7
April	3.4	7.4	5.4	11.1	3.3	0.1	0.2	0.15	5.9
May		0.7	0.35	1.2	0.1				0.3
Total	108.2	134.9	121.55	134.9	99.6	30.9	45.1	38	108.4
Precipitation									
June									
July									
August			0						
September		4.02	2.01	2.97					2.93
October	3.22	2.93	3.075	2.44	2.88	2.39	2.18	2.285	2.82
November	2.93	2.51	2.72	2.92	3.27	2.19	2.73	2.46	3.58
December	2.47	2.23	2.35	2.73	3.48	2.96	4.31	3.635	3.32
January	1.45	1.54	1.495	2.08	3.03	3.59	4.56	4.075	3.46
February	1.84	1.23	1.535	2.1	2.91	3.22	4.74	3.98	3.06
March	3.17	2.98	3.075	2.28	3.43	3.78	4.79	4.285	3.62
April	3.83	3.9	3.865	2.61	3.35	3.03	3.46	3.245	3.56
May		4.3	2.15	2.72	3.84				3.33
Total Winter Precip.	18.91	25.64	22.275	22.85	26.19	21.16	26.77	23.965	29.68
Total - end Mo									
Unadjusted Weathering Index, day-inches	2,046	3,459	2,708	3,082	2,609	654	1,207	911	3,217
Onset of Damage, yr			9.2	8.1	9.6			27.5	7.8
Roof Collapse Years			83	73	86			247	70

Table 2-2. Commercial reactor freeze/thaw data (8 of 13).

Reactor site number			45			46 & 47			48
Record (years)	30 Zion	30 Zion	Zion	30 Point Beach Kewaunee	30 Point Beach Kewaunee	Point Beach Kewaunee	30 Quad Cities	30 Quad Cities	Quad Cities
Freezing (days/month)	Milwaukee Wisconsin	Chicago Illinois	Average	Milwaukee Wisconsin	Green Bay Wisconsin	Average	Moline Illinois	Peoria Illinois	Average
June									
July									
August									
September	0.1	0.2	0.15	0.1	0.7	0.4	0.2	0.1	0.15
October	4.3	5.3	4.8	4.3	8.2	6.25	5.7	4.7	5.2
November	18	16.5	17.25	18	22.2	20.1	18.3	16.7	17.5
December	28	26.7	27.35	28	29.5	28.75	27.3	26.7	27
January	29.7	28.7	29.2	29.7	30.7	30.2	29.5	29.4	29.45
February	26.1	25	25.55	26.1	27.3	26.7	25.2	25.3	25.25
March	23.6	21	22.3	23.6	26.6	25.1	20.6	19.5	20.05
April	9.9	7.8	8.85	9.9	13.7	11.8	7.4	5.9	6.65
May	1.1	0.9	1	1.1	2.8	1.95	0.7	0.4	0.55
Total	140.8	132.1	136.45	140.8	161.7	151.25	134.9	128.7	131.8
Precipitation									
June									
July									
August									
September	3.38	3.82	3.6	3.38	3.47	3.425	4.02	3.87	3.945
October	2.41	2.41	2.41	2.41	2.23	2.32	2.93	2.65	2.79
November	2.51	2.92	2.715	2.51	2.16	2.335	2.51	2.69	2.6
December	2.33	2.47	2.4	2.33	1.53	1.93	2.23	2.44	2.335
January	1.6	1.53	1.565	1.6	1.15	1.375	1.54	1.51	1.525
February	1.45	1.36	1.405	1.45	1.03	1.24	1.23	1.42	1.325
March	2.67	2.69	2.68	2.67	2.05	2.36	2.98	2.91	2.945
April	3.5	3.64	3.57	3.5	2.4	2.95	3.9	3.77	3.835
May	2.84	3.32	3.08	2.84	2.82	2.83	4.3	3.7	4
Total Winter Precip.	22.69	24.16	23.425	22.69	18.84	20.765	25.64	24.96	25.3
Total - end Mo									
Unadjusted Weathering index, day-inches	3,195	3,192	3,196	3,195	3,046	3,141	3,459	3,212	3,335
Onset of Damage, yr			7.8			8.0			7.5
Roof Collapse Years			70			72			67

Table 2-2. Commercial reactor freeze/thaw data (9 of 13).

Reactor site number			50			51	52	53
Record (years)	30 North Anna	30 North Anna	North Anna	30 Joe M. Farley	30 Joe M. Farley	Joe M. Farley	30 Brunswick	Don Cook
Freezing (days/month)	Richmond Virginia	Lynchburg Virginina	Average	Montgomery Alabama	Tallahassee Florida	Average	Wilmington North Carolina	South Bend Indiana
June								
July								
August								
September								
October	2.1	2.5	2.3	0.3	0.2	0.25	0.2	3.2
November	9.4	9.6	9.5	3.9	3.9	3.9	3.2	14
December	19.2	19.9	19.55	10.6	9.7	10.15	11.3	25.6
January	23	23.4	23.2	14	11.2	12.6	14.3	28.3
February	19.5	20.4	19.95	8.8	7.8	8.3	10.9	24.5
March	10.8	11:9	11.35	2.5	3.1	2.8	3.8	19.9
April	2.3	2.8	2.55	0.1	0.2	0.15	0.3	8.1
May	0.1	0.1	0.1					0.8
Total	86.4	90.6	88.5	40.2	36.1	38.15	44	124.4
Precipitation								
June								
July								
August								
September								
October	3.53	3.7	3.615	2.45	2.92	2.685	2.69	3.09
November	3.17	3.14	3.155	4.06	3.87	3.965	3.11	3.27
December	3.26	3.23	3.245	5.2	5.03	5.115	3.63	3.3
January	3.24	2.86	3.05	4.68	4.77	4.725	3.87	2.23
February	3.16	3.04	3.1	5.48	5.56	5.52	3.7	1.9
March	3.61	3.47	3.54	6.26	6.21	6.235	3.88	3.1
April	2.96	3.09	3.025	4.49	3.74	4.115	2.87	3.82
May	3.84	3.91	3.875					3.22
Total Winter Precip.	26.77	26.44	26.605	32.62	32.1	32.36	23.75	23.93
Total - end Mo								
Unadjusted Weathering Index, day-inches	2,313	2,395	2,355	1,311	1,159	1,235	1,045	2,977
Onset of Damage, yr			10.6			20.3	23.9	8.4
Roof Collapse Years			96			182	215	76

EIS Related Information

Table 2-2. Commercial reactor freeze/thaw data (10 of 13).

Reactor site number			54	55	56 & 57			58	59
Record (years)	30 Palisades	30 Palisades	Palisades	30 Commanche Peak	30 Fitzpatric Nine Mile Point	30 Calvert Cliffs	30 Calvert Cliffs	Calvert Cliffs	30 Fort Calhoon
Freezing (days/month)	South Bend Indiana	Grand Rapids Michigan	Average	Dallas Texas	Syracuse New York	Washingtom DC	Baltimore Maryland	Average	Omaha Nebraska
June									
July									
August									
September		0.3	0.15		0.2				0.4
October	3.2	6.1	4.65		4.8	0.4	1.9	1.15	5.8
November	14	17.3	15.65	2.3	14.8	4.2	10.2	7.2	20.2
December	25.6	27.9	26.75	10.7	26.6	15.7	21.1	18.4	29.3
January	28.3	29.4	28.85	15.7	28.8	22.3	25.3	23.8	30.2
February	24.5	26.1	25.3	9.3	25.2	18.5	21.1	19.8	26
March	19.9	23.9	21.9	2.8	23.7	8.4	14	11.2	21
April	8.1	11.9	10	0.2	11.8	0.9	3.4	2.15	6.7
May	0.8	2.2	1.5		1				0.4
Total	124.4	145.1	134.75	41	136.9	70.4	97	83.7	140
Precipitation									
June									
July									
August									
September		4.24	2.12		3.79				3.72
October	3.09	2.81	2.95		3.24	3.02	2.98	3	2.28
November	3.27	3.32	3.295	2.29	3.72	3.12	3.32	3.22	1.49
December	3.3	2.85	3.075	1.84	3.2	3.12	3.41	3.265	1.02
January	2.23	1.83	2.03	1.83	2.34	2.72	3.05	2.885	0.74
February	1.9	1.42	1.66	2.18	2.15	2.71	3.12	2.915	0.77
March	3.1	2.63	2.865	2.77	2.77	3.17	3.38	3.275	2.04
April	3.82	3.37	3.595	3.5	3.33	2.71	3.09	2.9	2.66
May	3.22	3.13	3.175		3.28				4.52
Total Winter Precip.	23.93	25.6	24.765	14.41	27.82	20.57	22.35	21.46	19.24
Total - end Mo									
Unadjusted Weathering Index, day-inches	2,977	3,715	3,337	591	3,809	1,448	2,168	1,796	2,694
Onset of Damage, yr			7.5	42.3	6.6			13.9	9.3
Roof Collapse Years			67	381	59			125	84

Table 2-2. Commercial reactor freeze/thaw data (11 of 13).

Reactor site number			60			61	62	63	64	65	66
Record (years)	30			30	30		30	30	30	30	30
	Cooper Nuc Station		Cooper Nuc Station	Davis Besse	Davis Besse	Davis Besse	Browns Ferry	Diablo Canyon	Oconee	South Texas Project	Prairie Island
Freezing (days/month)	Omaha Nebraska	Kansas City Missouri	Average	Toledo Ohio	Cleveland Ohio	Average	Huntsville Alabama	Santa Maria California	Greenville South Carolina	Victoria Texas	Minneapolis Minnesota
June											
July											
August											
September	0.4		0.2	0.4		0.2					0.5
October	5.8	2.2	4	7.1	2.8	4.95	0.6	0.2	0.9		7.4
November	20.2	13.5	16.85	17.4	12.5	14.95	7.2	1.6	6.6	0.6	23.4
December	29.3	26.4	27.85	26.8	24.8	25.8	16.4	6.2	15.4	3.3	30.1
January	30.2	28.1	29.15	29.2	27.9	28.55	19.9	6.6	19	5.3	30.9
February	26	21.9	23.95	25.5	24.3	24.9	14.2	3.2	15.3	2.5	27
March	21	14.3	17.65	22.5	21	21.75	6.8	1.7	7.2	0.5	25.1
April	6.7	3.8	5.25	11.4	9.3	10.35	0.8	0.5	1		11.1
May	0.4	0.1	0.25	1.7	0.9	1.3		0.1			1.1
Total	140	110.3	125.15	142	125.5	132.75	65.9	20.1	65.4	12.2	156.6
Precipitation											
June											
July											
August											
September	3.72		1.86	2.85		1.425					2.72
October	2.28	3.29	2.785	2.1	2.54	2.32	3.25	0.49	3.99		2.19
November	1.49	1.92	1.705	2.81	3.17	2.99	4.86	1.46	3.65	2.45	1.55
December	1.02	1.58	1.3	2.93	3.09	3.01	5.87	1.78	4.14	2.04	1.08
January	0.74	1.09	0.915	1.75	2.04	1.895	5.17	2.16	4.1	2.16	0.95
February	0.77	1.1	0.935	1.73	2.19	1.96	4.87	2.62	4.41	2	0.88
March	2.04	2.51	2.275	2.66	2.91	2.785	6.62	2.27	5.39	1.55	1.94
April	2.66	3.12	2.89	2.96	3.14	3.05	4.92	0.99	3.86		2.42
May	4.52	5.04	4.78	2.91	3.49	3.2		0.2			3.39
Total Winter Precip.	19.24	19.65	19.445	22.7	22.57	22.635	35.56	11.97	29.54	10.2	17.12
Total - end Mo											
Unadjusted Weathering Index, day-inches	2,694	2,167	2,434	3,223	2,833	3,005	2,343	241	1,932	124	2,681
Onset of Damage, yr			10.3	7.8	8.8	8.3	10.7	103.9	12.9	200.9	9.3
Roof Collapse Years			92	70	79	75	96		116		84

EIS Related Information

Table 2-2. Commercial reactor freeze/thaw data (12 of 13).

Reactor site number	67	68	69	70	71	72	73				74
Record (years)	30	30	30	30	30	30	50		4	30	30
	Shearson Harris	Limerick	Vermont Yankee	Seabrook	Surry	Susquehana	Washington Nuclear Power	Savannah River Site	Yucca Mt.	Las Vegas	Lacrosse
	Raleigh North Carolina	Philadelphia Pennsylvania	Albany New York	Portland Maine	Norfolk Virginia	Wilkes-Barre Scranton Pennsylvania	PNNL 11471 Hanford Site	G-SAR-00001 SRS			La Crosse Wisconsin
Freezing (days/month)											
June											
July											
August											
September			0.7	0.8							0.4
October	1.6	1.5	8.4	8.6	0.2	4.3	4	0.1		0.1	6.7
November	9.1	8.5	18.1	19.3	3	13.6	15	3.6	7	2.2	20.6
December	17.8	21.2	27.7	28.9	13.1	25.1	24	8.9	12	11.4	29.4
January	20.8	26.2	29.6	29.9	18	28	26	12.2	9.7	13	30.7
February	17.4	22.3	25.9	26.5	15.5	24.3	20	9.1	7.3	4.7	27
March	9.5	14	24.4	25.2	6	20.8	14	3.3	2	1.3	24.7
April	2.3	2.6	12.5	13.5	0.4	8.2	4	0.1		0.1	10
May	0.1		1.7	2		0.6					0.9
Total	78.6	96.3	149	154.7	56.2	124.9	107	37.3	38	32.8	150.4
Precipitation											
June											
July											
August											
September			2.95	3.09							3.79
October	2.86	2.62	2.83	3.9	3.15	2.79	0.39	2.49		0.21	2.2
November	2.98	3.34	3.23	5.17	2.85	3.06	0.91	2.6	0.24	0.43	1.73
December	3.24	3.38	2.93	4.55	3.23	2.51	1.03	3.63	0.45	0.38	1.27
January	3.48	3.21	2.36	3.53	3.78	2.1	0.79	4.17	0.92	0.4	0.93
February	3.69	2.79	2.27	3.33	3.47	2.15	0.62	4.61	0.61	0.48	0.9
March	3.77	3.46	2.93	3.67	3.7	2.55	0.47	5.02	0.9	0.42	1.98
April	2.59	3.62	2.99	4.08	3.06	2.97	0.41	3.49		0.21	2.88
May	3.92		3.41	3.63		3.65					3.26
Total Winter Precip.	26.53	22.42	25.9	34.95	23.24	21.78	4.62	26.01	3.12	2.53	18.94
Total - end Mo											
Unadjusted Weathering Index, day-inches	2,085	2,159	3,859	5,407	1,306	2,720	494	970	119	83	2,849
Onset of Damage, yr	12.0	11.6	6.5	4.6	19.1	9.2	50.6	25.8	210.9	301.3	8.8
Roof Collapse Years	108	104	58	42	172	83	455	232	1898	2711	79

EIS Related Information

Table 2-2. Commercial reactor freeze/thaw data (13 of 13).

Reactor site number					
Record (years)		30	30		30
	INEEL				Fort St Vrain
	SAR for TM-2 ISNFSI				
	INEEL	Boise Idaho	Salt lake City Utah	Average	Denver Colorado
Freezing (days/month)					
June	1			0.333333333	
July				0.00	
August				0.00	
September	7	0.6	0.4	2.67	0.8
October	22	5.8	4.7	10.83	8.5
November	23	16.5	17.8	19.10	24.5
December	14	25.3	27.5	22.27	29.2
January	10	25.7	27.4	21.03	29.8
February	16	19.5	22.6	19.37	25.9
March	25	17	16.3	19.43	24.2
April	22	8.9	6.5	12.47	11.4
May	9	2.1	0.8	3.97	1.5
Total	149	121.4	124	131.47	155.8
Precipitation					
June	1.18			0.39	
July				0.00	
August				0.00	
September	0.63	0.8	1.28	0.90	1.24
October	0.52	0.75	1.44	0.90	0.98
November	0.68	1.48	1.29	1.15	0.87
December	0.75	1.36	1.4	1.17	0.64
January	0.69	1.45	1.11	1.08	0.5
February	0.64	1.07	1.23	0.98	0.57
March	0.6	1.29	1.91	1.27	1.28
April	0.73	1.24	2.12	1.36	1.71
May	1.2	1.08	1.8	1.36	2.4
Total Winter Precip.	7.62	10.52	13.58	10.57333333	10.19
Total - end Mo					
Unadjusted Weathering index, day-inches	1,135	1,277	1,684	1,390	1,588
Onset of Damage, yr	22.0	19.6	14.8	18.0	15.7
Roof Collapse Years	198	176	134	162	142

2.2 Concrete Degradation Aboveground Storage Facilities from Chemical Attack Analysis

For degradation of concrete resulting from chemical attack (from chemicals present in precipitation), the following processes were evaluated: sulfate and magnesium attack, calcium leaching, carbonation, chloride penetration, and rebar corrosion. To determine the rate at which chemical reactions would occur, it was necessary to determine the chemical composition of the concrete (Reference 4). The chemical concentration was determined from calculating the composition of each chemical in several types of concrete commonly utilized in construction. The density of the concrete was assumed to be 2.7 grams/cm^3.

The chemical (i.e., chlorides, etc.) composition of the precipitation was taken from the data associated with the Savannah River Site (SRS) near Barnwell, South Carolina. The precipitation chemistry data (Table 2-3) were obtained by daily sampling although only the yearly averages for 1996 and 1997 are listed.

Table 2-3. Precipitation chemistry for Barnwell, South Carolina.[a]

	Average for year	
Chemistry[b]	1996	1997
PH	4.542	4.588
Fluoride, μg/mg	0.062	0.018
Chloride	0.947	0.455
Bromine	0.000	0.000
Nitrate	1.072	0.830
Phosphate	0.000	0.000
Sulfate	1.681	1.435
Sodium	0.320	0.235
Ammonium	0.134	0.181
Potassium	0.000	0.000
Calcium	0.021	0.054

a. Information from Reference 5.
b. Chemical units are μg/mg; pH has no units.

The concrete degradation processes are discussed in Reference 2. The formulae used in Sections 2.2.2.1 through 2.2.2.5 analyze the rate chemical attack on surface concrete storage modules.

2.2.1 CONCRETE DEGRADATION FOR UNDERGROUND CONCRETE VAULTS (FROM SECTION 4.2.2 OF REFERENCE 2)

An analysis of concrete damage indicates that the predominate failure mechanism for an underground concrete vault is a combination of physical, chemical, and mechanical forces. Physical and mechanical degradation processes that produce cracking are of primary concern because the permeability increases and shielding is potentially lost. The chemistry of groundwater would affect the degradation of the underground facility. The major sources of sulfate and magnesium in SRS groundwater are from weathering of rock minerals by rainfall. Concentrations of sulfate and magnesium in groundwater at SRS are very low. Sulfate concentrations range from 0.27 to 15 ppm (2.81×10^{-6} to 1.56×10^{-4} mol/L) with a mean and median of 3.66 and 2 ppm (3.81×10^{-5} and 2.08×10^{-5} mol/L), respectively. Magnesium concentrations range from 0.14 to 8 ppm (5.76×10^{-6} to 3.29×10^{-4} mol/L), with a mean and medium of 2.28 and 1.5 ppm (9.37×10^{-5} and 6.17×10^{-5} mol/L), respectively. The sum of Mg and SO_4 range from

0.57 to 18.5 ppm (1.51×10^{-5} to 3.77×10^{-4} mol/L) with a mean and median of 5.94 and 4.95 ppm (1.32×10^{-4} and 1.08×10^{-4} mol/L), respectively (Reference 2).

The principal chemical processes that may disrupt the integrity of concrete structures are carbonation, calcium hydroxide leaching, and rebar corrosion. Each of these is discussed in Appendix B of Reference 2. Each was evaluated for the operating floor (or roof of vault) and the walls and floor of the vault at 1,000 and 10,000 years. (See Table 2-4 for results of this analysis.) The major failure was shown to be cracking and collapse of the operating floor after 3,200 years. Freeze/thaw damage was not evaluated because it was considered a minor consequence for subsurface structures, especially at SRS.

Table 2-4. Concrete damage in underground concrete facilities.

	Expected depth of concrete damage	
Degradation mechanism	1,000 years damage	10,000 years damage
Sulfate and magnesium attack	1 cm	5 cm
Carbonation	Reflected in reinforcing bar corrosion	Reflected in reinforcing bar corrosion
Calcium hydroxide leaching	5 cm	23 cm
	Time to cracking of operating floor from stress increases from concrete loss (years)	
Concrete loss	1,600	
	Time to roof collapse (years)	
Reinforcing bar corrosion (average loss or bar cross sectional area at 1,000 year - ~40%)	3,200	

2.2.2 CONCRETE DEGRADATION FOR SURFACE CONCRETE FACILITIES

The section has five parts that describe chemical degradation mechanisms for surface concrete facilities resulting from long-term exposure to precipitation. Both the description of the surface concrete facilities and the degradation mechanism are discussed in Reference 2. These five subsections apply the mechanisms to the concrete failure.

2.2.2.1 Sulfate and Magnesium Attack

The rate of surface loss due to sulfate and magnesium attack was calculated using the following formula:

$$X = 0.55\, C_S\, (Mg\ 2+ + SO_4\ 2-)t$$

where

X	=	distance of corrosion into concrete (cm)
C_S	=	C_3A (concrete gel) concentration in solid (mole/cm^3)
C_{mg}	=	Mg concentration in solution (mole/liter)
C_{SO_4}	=	SO_4 concentration in solution (mole/liter)
t	=	time(s)

The amount of concrete damaged due to this sulfate and magnesium attack is shown in the second column of Table 2-5. As can be seen from this table, the sulfate and magnesium attack is very low.

2.2.2.2 Calcium Hydroxide Leaching

Where concrete is exposed to water, constituents in the concrete are leached. Alkalis are leached first, followed by calcium hydroxide. This process can be described in four stages:

1. Initially, the pH of standard concrete is approximately 13 due to the presence of alkali metal oxides and hydroxides. These alkali metals leach first.

2. After the alkali metals are leached, the pH is controlled at 12.5 by solid calcium hydroxide. Free (not bound by C-S-H gel) calcium hydroxide is leached first.

3. Following loss of free calcium hydroxide, calcium hydroxide is leached at a slower rate from the C-S-H gel. The C-S-H gel dissolves incongruously, while the pH drops to 10.5 and the calcium to silicon ratio drops to 0.85.

4. The pH is held to 10.5 by congruent dissolution of the C-S-H gel.

Ingress of water onto the concrete surface provides a pathway for leaching of soluble components from the concrete. This leaching of calcium hydroxide from the concrete leads to loss of strength. The rate of leaching was estimated using numerical models shown below that assumed concrete-controlled and geology-controlled leaching, respectively:

$$X_C = \left(2D_i \frac{C_i - C_{gw}}{C_s} t \right)^{1/2},$$

and

$$X_G = 2\phi \frac{C_i - C_{gw}}{C_s} \left(\frac{R_d D_E t}{\pi} \right)^{1/2},$$

where,

X_c	=	depth of leach penetration due to concrete-controlled leaching (cm),
X_G	=	depth of leach penetration due to geology-controlled leaching (cm),
D_i	=	intrinsic diffusion coefficient of Ca^{++} in concrete (cm^2/s),
C_i	=	Ca^{++} concentration in concrete pore water ($mole/cm^3$),
C_{gw}	=	Ca^{++} concentration in ground/soil water ($mole/cm^3$),
C_s	=	bulk Ca^{++} concentration in concrete solid ($mole/cm^3$),
ø	=	porosity of soil (unitless),
R_d	=	retardation coefficient (unitless),
D_E	=	effective dispersivity/diffusivity of Ca^{++} in the surrounding geological material (cm^2/s), and
t	=	time in seconds.

The rate of penetration of concrete is shown in the third column of Table 2-5.

Table 2-5. Concrete degradation (inches) - no freeze/thaw degradation.

Time, Years	Sulfate & Magnesium Attack	Calcium Leaching	Carbonation	Chloride Penetration	Rebar Corrosion	Total inches of Degradation	
10	0.002	0.030	0.0004	0.050		0.082	
100	0.020	0.094	0.0012	0.331		0.446	
1,000	0.216	0.297	0.0039	2.187		2.703	
1,500	0.323	0.363	0.0047	3.049	starts	3.740	
2,000	0.431	0.419	0.0055	3.859		4.715	
2,500	0.539	0.469	0.0061	4.634	75% remaining	5.648	
3,000	0.647	0.514	0.0067	5.381		6.548	
3,500	0.754	0.555	0.0072	6.106	50% remaining	7.422	
4,000	0.862	0.593	0.0077	6.812		8.275	
4,500	0.970	0.629	0.0082	7.502	25% remaining	9.109	
5,000	1.078	0.663	0.0086	8.179	0% remaining	9.928	
5,500	1.185	0.696	0.0091	8.843		10.733	
6,000	1.293	0.726	0.0095	9.497		11.526	
6,500	1.401	0.756	0.0099	10.141		12.308	
7,000	1.509	0.785	0.0102	10.776		13.080	
7,500	1.616	0.812	0.0106	11.403		13.842	
8,000	1.724	0.839	0.0109	12.023		14.597	
8,500	1.832	0.865	0.0113	12.635		15.343	
9,000	1.940	0.890	0.0116	13.241		16.082	
9,500	2.047	0.914	0.0119	13.841		16.815	
10,000	2.155	0.938	0.0122	14.436		17.541	Half thickness reached
20,000	4.310	1.326	0.0173	25.479		31.133	
30,000	6.465	1.624	0.0212	35.524		43.635	
50,000	10.775	2.097	0.0273	53.997		66.897	full thickness
100,000	21.550	2.966	0.0387	95.304		119.859	exceeded

2.2.2.3 Carbonation

Carbonation occurs when calcium in concrete reacts with carbon dioxide (CO_2) to form calcium carbonate according to the following reaction.

$$Ca(OH)_2 + H_2O + CO_2 \Rightarrow CaCO_3 + 2(H_2O)$$

The following analytic expression was employed for estimating carbonation rate in the degradation model:

$$X = \left(2D_i \frac{C_{gw}}{C_g} t\right)^{1/2},$$

where,

X	=	depth of penetration of carbonation (cm)
D_i	=	intrinsic diffusion coefficient of Ca^{++} in concrete (cm^2/s)
C_{gw}	=	total inorganic carbon in groundwater or soil moisture ($mole/cm^3$)
C_g	=	$Ca(OH)_2$ bulk concentration in concrete solid ($mole/cm^3$) and
t	=	time (s)

The fourth column of Table 2-5 shows the rate of carbonation for the surface concrete storage modules. This mode of degradation is much slower than the calcium leaching.

2.2.2.4 Chloride Penetration

Chloride from atmospheric chloride and from chlorides scavenged from the air and contained in precipitation was evaluated and found to be the predominant cause of surface concrete degradation (if the concrete was not exposed to freeze/thaw mechanisms as discussed in Section 2.1) for thick walled structures like the concrete storage modules.

The chlorides react with the alkali metal oxides in the concrete causing a lack of strength of the concrete. Loss of alkali metal oxides in concrete essentially convert the concrete to sand and gravel-like components. The degradation formulae for concrete were discussed in Reference 2 as penetration time for initiation time of corrosion of reinforcing bar. The following formula was given in that reference and can be used to predict the rate of chloride penetration. By rearranging the equation one can use it to determine the depth of chloride penetration. The equation given below is the same equation as used in Section 2.2.2.5 to measure onset of reinforcing bar corrosion.

$$t_c = \frac{129 X_c^{1.22}}{WCR * Cl^{0.42}},$$

where,

t_c	=	time of corrosion (yr),
X_c	=	depth of penetration of concrete (inches),
WCR	=	water-cement ratio in concrete (kg/kg), and
Cl	=	chloride ion concentration in precipitation (ppm).

The fifth column of Table 2-5 shows the calculated chloride penetration of the concrete.

2.2.2.5 Rebar Corrosion

Reinforcing steel (commonly called rebar) is used in concrete structures to increase tensile strength of the structure. Corrosion of the rebar is another possible mechanism of vault degradation. Corrosion occurs when iron in the rebar reacts with oxygen to form iron oxides. Corrosion of the rebar lowers the strength of the rebar and disrupts the integrity of the surrounding concrete. As the rebar corrodes, the tensile strength of the structure declines.

The analysis of failure of the surface concrete storage modules were evaluated to see when the reinforcing steel might be lost and what the consequence of loss of this rebar was to the integrity of the modules.

Corrosion of steel reinforcement results in a loss of cross-sectional area of the rebar. Thus, the corrosion of reinforcing steel due to oxygen diffusion occurs in two steps. First, the passivating layer must be broken down before the onset of corrosion. The time to onset of corrosion was approximated by:

$$t_c = \frac{129Xc^{122}}{WCR * C1^{0.42}},$$

where,

- t_c = time to onset of corrosion (yr),
- X_c = thickness of concrete over rebar (inches),
- WCR = water-cement ratio in concrete (kg/kg), and
- C1 = chloride ion concentration in groundwater (ppm).

The reaction then proceeds, with a loss of reinforcing steel volume approximated by:

$$\%\,\text{Re bar Re maining} = 100\left(1-\left(\frac{4 * 9.4\left(\frac{cm^3}{mole}\right)sDiCs(t-tc)}{\pi d^2 \Delta X}\right)\right)$$

where,

- s = spacing between reinforcement bars (cm),
- D_i = oxygen diffusion coefficient in concrete (cm^2/s),
- C_{gw} = oxygen concentration in groundwater ($mole/cm^3$),
- t = time (s),
- d = diameter of rebar (cm),
- ΔX = depth of rebar below surface (in), and
- Cs = bulk Ca concentration in concrete solid (mols/cm).

The sixth column of Table 2-5 shows that oxidation of the upper course of rebar in the concrete storage modules (CSM) would start in 1,500 years after lost of institutional control and that in 5,000 years all of that upper course of reinforcing rod would have converted to iron oxide and provide no strength to the CSM.

A structural analysis was performed to see what reliance had to be placed on the strength of the upper course of rebar. The analysis indicates that the upper rebar is unnecessary to support the surface loads on the CSM even if all of the degradation products of the concrete were still in place. The total load is easily carried by the lower course of rebar. They were stressed only at 30 percent of yield stress for the steel.

The analysis concludes that the loss of the upper course of reinforcing rod has no effect on CSM collapse. By way of contrast, this is the predominant failure mode for underground reinforced concrete vaults like those discussed in Section 2.2.1.

3.0 National Precipitation

Mean annual precipitation (Reference 6) for the United States was subdivided by precipitation ranges was used in the analysis. Emphasis was placed on the eastern and western parts of the United States where storage facilities might exist. Figure 3-1 shows the precipitation regions used. Table 3-1 shows the nuclear sites that are affected in the continued storage analysis. Table 3-2 provides typical rainfall for the various sites within the <30" precipitation range and defines the mean as 10.5". Table 3-3 gives other precipitation data for the five regions used in the degradation analysis.

4.0 Precipitation Chemistry

Information on precipitation chemistry was required for the analysis to determine the deterioration of the engineered barriers and SNF and HLW. Precipitation chemistry includes pH, sodium, chloride, nitrate, sulfate, ammonium, calcium, magnesium, and potassium ions. There have been significant decreases in the cation concentration over the last 12 years (Reference 7). Due to the changes experienced in precipitation, the precipitation chemistry was developed from 1994-1996 data. These data were available from USGS National Atmospheric Deposition Program/National Trends Network (NADP/NTN) Web Page (Reference 8). Figures 4-1 through 4-8 present the chemical precipitation concentrations for pH, sodium, chloride, nitrate, sulfate, ammonium, calcium, magnesium, and potassium ions, respectively. Table 4-1 was constructed from these figures using the range midpoint.

5.0 Relative Humidity

Information on relative humidity was required to predict the corrosion rate of engineered barriers. The relative humidity data for the sites was obtained from "Local Climatological Data" reports for 1996 (Reference 3). These data are compiled by the National Oceanic and Atmospheric Administration and published annually. The report contains both annual data and average for the previous 30 years. The data used in this analysis are the 30-year data. Battelle Pacific Northwest Division developed the corrosion models used in determining degradation of the stainless steel engineered barrier. In Reference 9, they conclude corrosion of stainless steel proceeds at humidities ≥85 percent.

The 30-year climatological data for relative humidity are given for 4 6-hour periods/month. Analysis determined the number of 6-hour periods per month when the relative humidity exceeded 85 percent. These are shown in Table 5-1 along with the calculated percent of the year that the relative humidity exceeded 85 percent. These data were combined with the percent of the year that had precipitation days in Reference 10. This information was used to determine stainless steel corrosion.

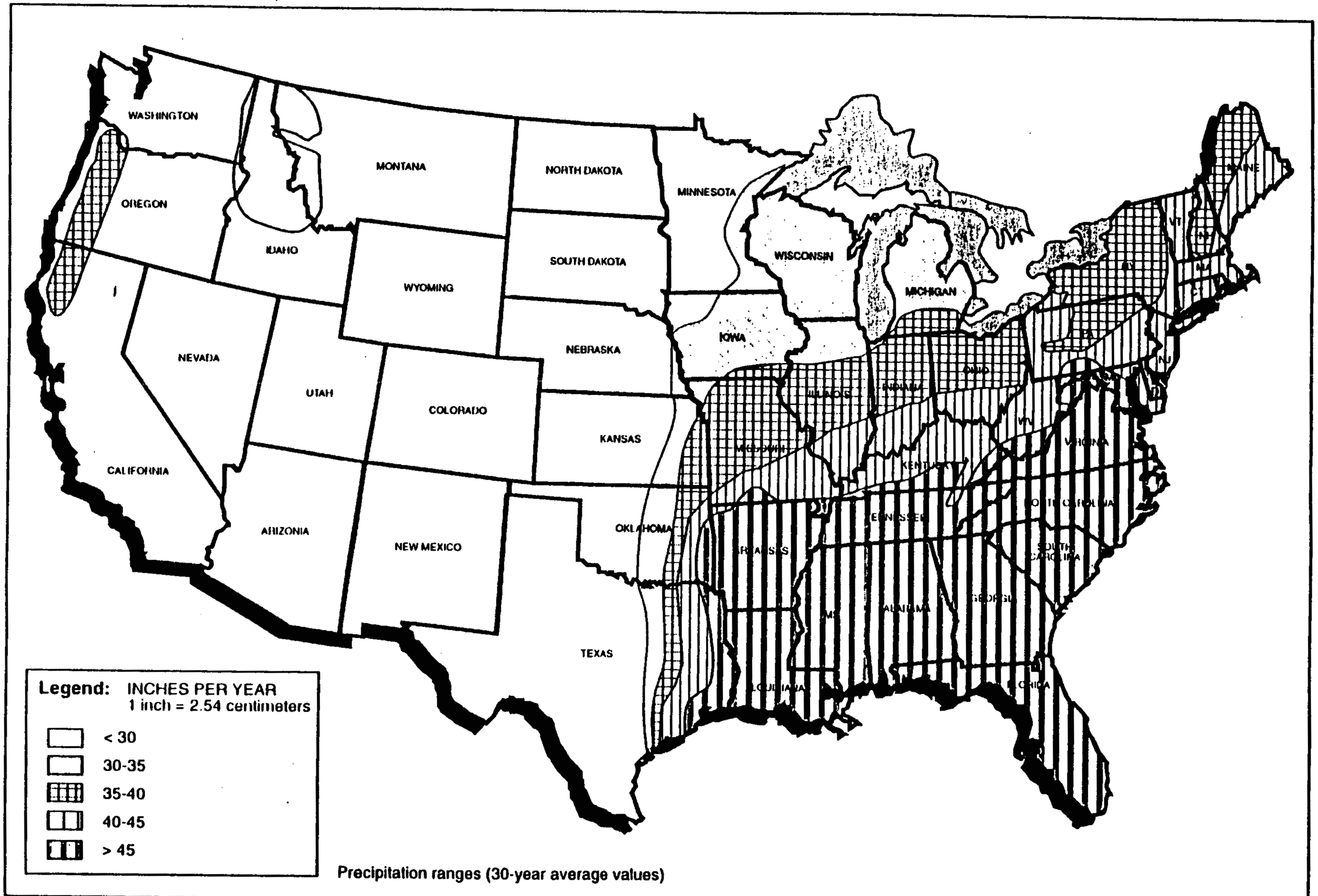

Figure 3-1. Regional precipitation.

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Table 3-1. Nuclear sites in various precipitation regions.

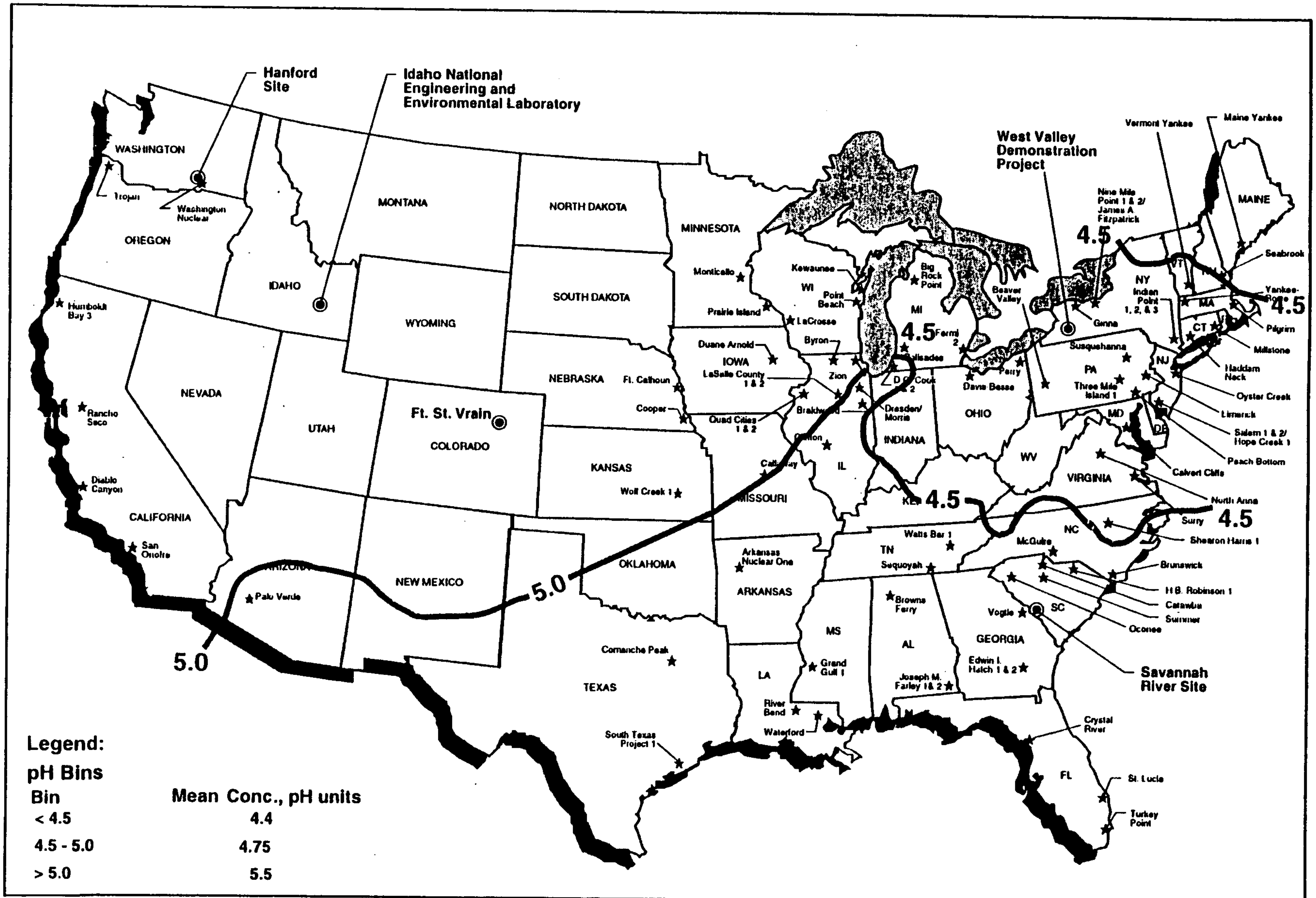
<30 inches/yr	30-35 inches/yr	35-40 inches/yr	40-45 inches/yr	>45 inches/yr
Diablo Canyon	Big Rock Point	Callaway	Beaver Valley	Arkansas Nuclear
Fort St. Vrain	Braidwood	Clinton	Haddam Neck	Bellefonte (not started up)
Palo Verde	Byron	Davis Besse	Hope Creek	Browns Ferry
Rancho Seco	Comanche	Humboldt Bay	Indian Point	Brunswick
San Onofre	Cooper Station	James A. Fitzpatrick	Limerick	Calvert Cliffs
Washington Nuclear Power	Donald C. Cook	Nine Mile Point	Maine Yankee	Catawba
Hanford	Dresden/Morris	Perry	Millstone	Crystal River
Yucca Mountain	Duane Arnold	Trojan	Oyster Creek	Grand Gulf
Idaho National Environmental & Engineering Laboratory	Fermi	Yankee-Rowe	Peach Bottom	Hatch
	Fort Calhoun	West Valley Demonstration Project	Pilgrim	H. B. Robinson
	Kewaunee		Salem	Joseph M. Farley
	Lacrosse		South Texas	McGuire
	La Salle		Susquehanna	North Anna
	Montecello		Three Mile Island	Oconee
	Palisades		Vermont Yankee	River Bend
	Point Beach			Savannah River Site
	Prairie Island			Sequoyah
	Quad Cities			Shearon Harris
	Seabrook			St. Lucie
	Wolf Creek			Summer
	Zion			Surry
				Turkey Point
				Vogtle
				Waterford
				Watts Barr

Table 3-2. Annual precipitation (inches/yr) at sites with less than 30 inches of precipitation.

Site	Location	Precipitation inches per year
Rancho Seco	Sacramento, CA	22.4
Diablo Canyon	Santa Maria, CA	12.4
San Onofre	San Diego, CA	10.9
Palo Verde	Phoenix, AZ	7.6
WNP-2 & 3	Richland, WA	8.2
Hanford	Richland, WA	8.2
Yucca Mountain	Las Vegas, NV	4.13
INEEL	Idaho Falls, ID	7.62
Fort St. Vrain	Denver, CO	16.1
Mean		10.5

Table 3-3. Precipitation rates for analysis.

Precipitation regions	<30	30-35	35-40	40-45	>45
Average Yearly Conditions					
Total Precipitation, in.	11	32.5	37.25	42.5	50
Days with precipitation	86	120	122	110	107
Dry days	279	236	244	246	249
Daily Precipitation (in./24 hours)					
Maximum (50 year recurrence)	1.74	5.07	5.81	6.63	7.80
Average	0.131	0.271	0.333	0.386	0.467
Hourly Precipitation (in./single hour)					
Maximum (50 year recurrence)	0.76	2.21	2.53	2.89	3.40
Average	0.0054	0.0113	0.0139	0.0161	0.0195



YUCCA MTN EIS/Pubsonly/Grfx/Nat Weather SNF & HLW/4-1 pH Isopleth.AI

Figure 4-1. pH Isopleths.

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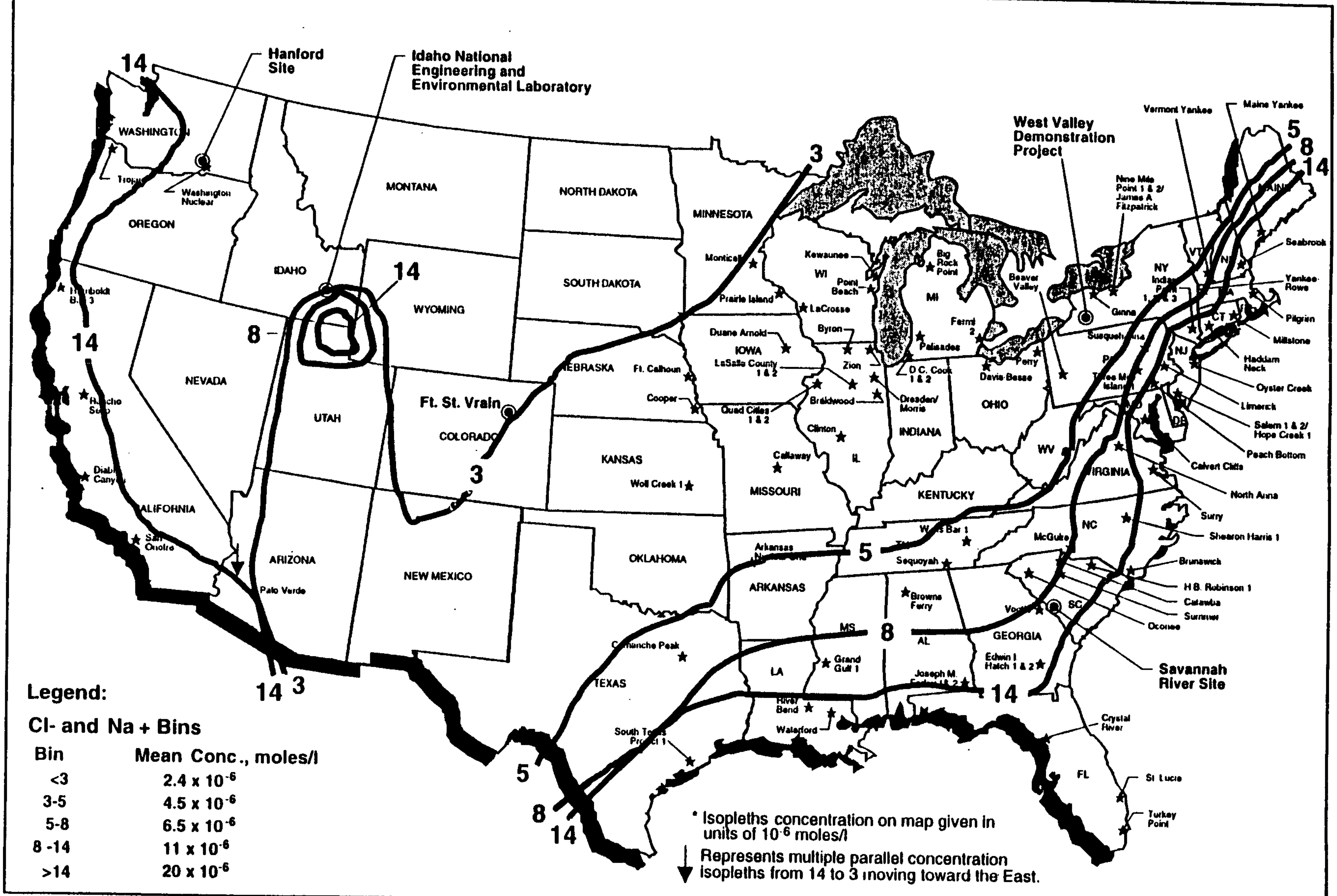

Figure 4-2. Chloride and Sodium Concentration Isopleths*.

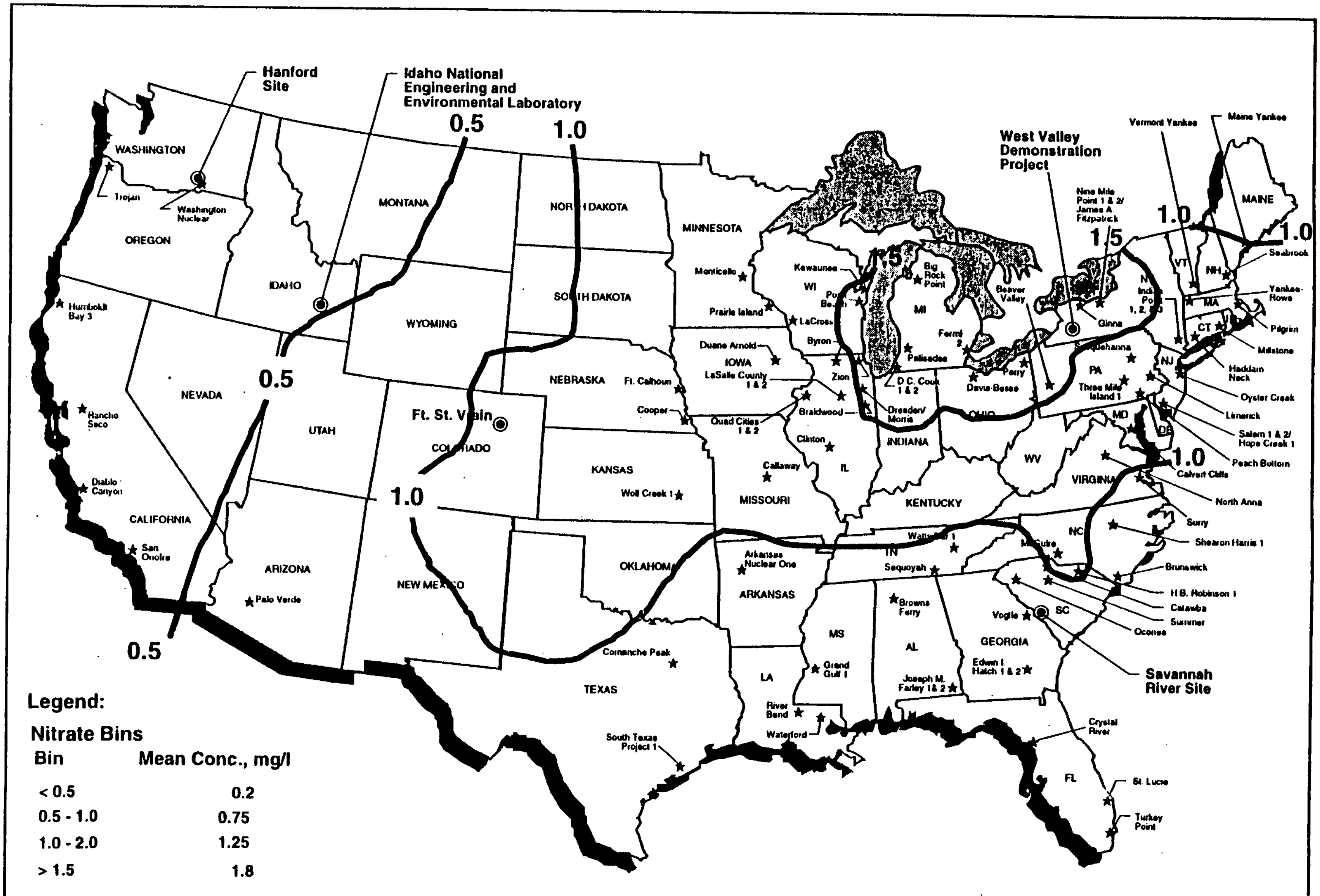

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Figure 4-3. Nitrate Ion Concentration Isopleths.

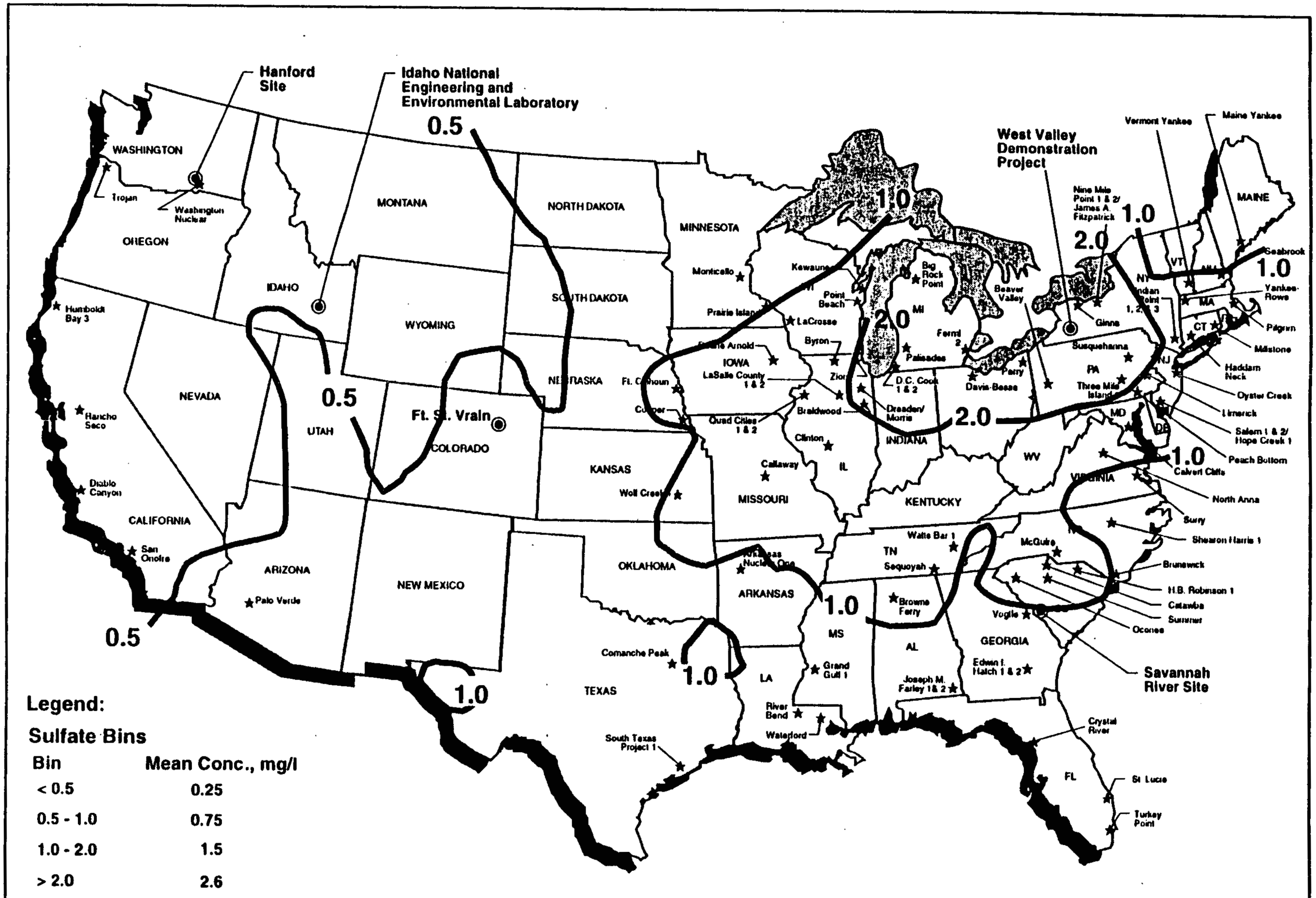

Figure 4-4. Sulfate Ion Concentration Isopleths.

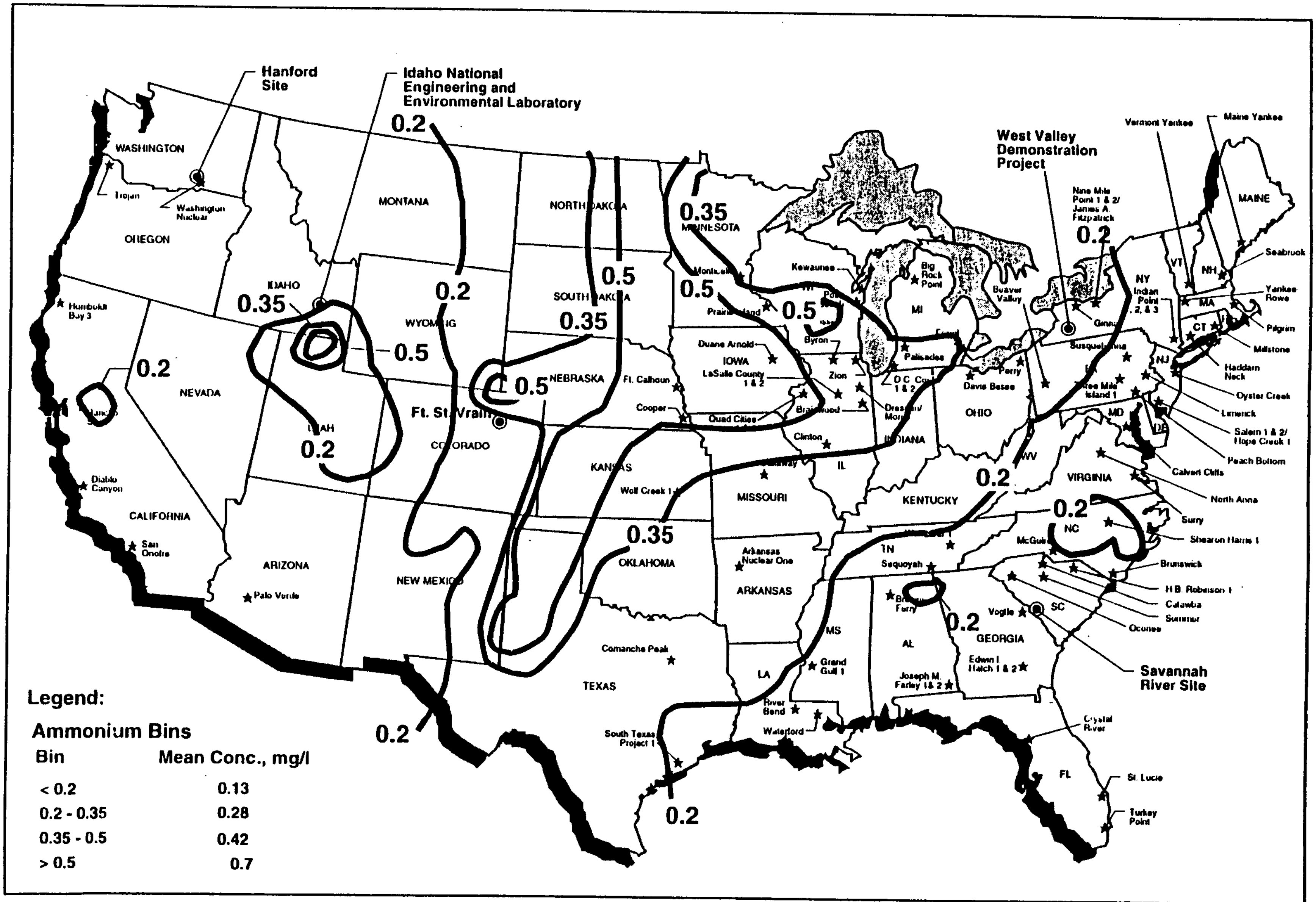

Figure 4-5. Ammonium Ion Concentration Isopleths.

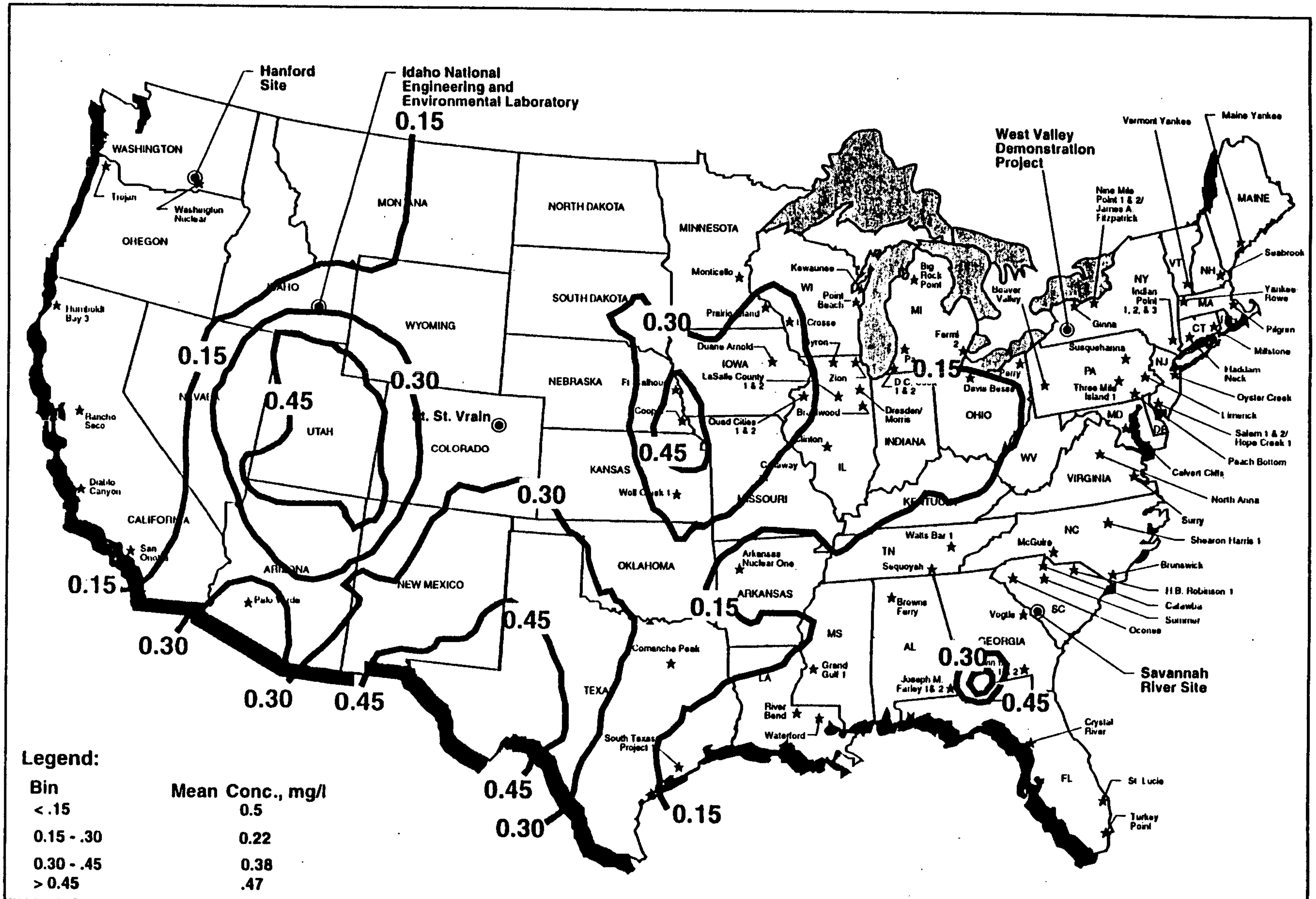

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Figure 4-6. Calcium Ion Concentration Isopleths.

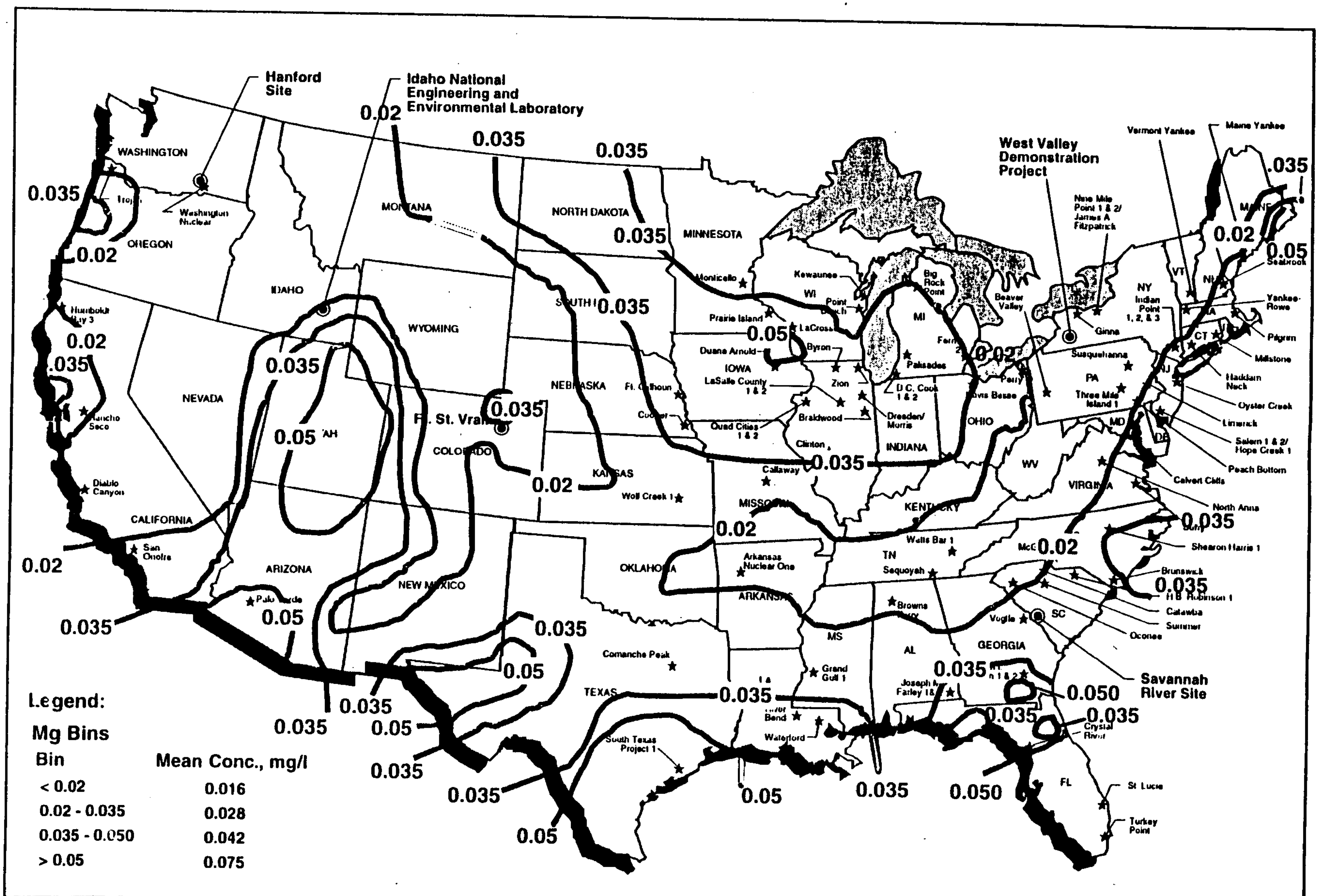


Figure 4-7. Magnesium Ion Concentration Isopleths.

EIS Related Information

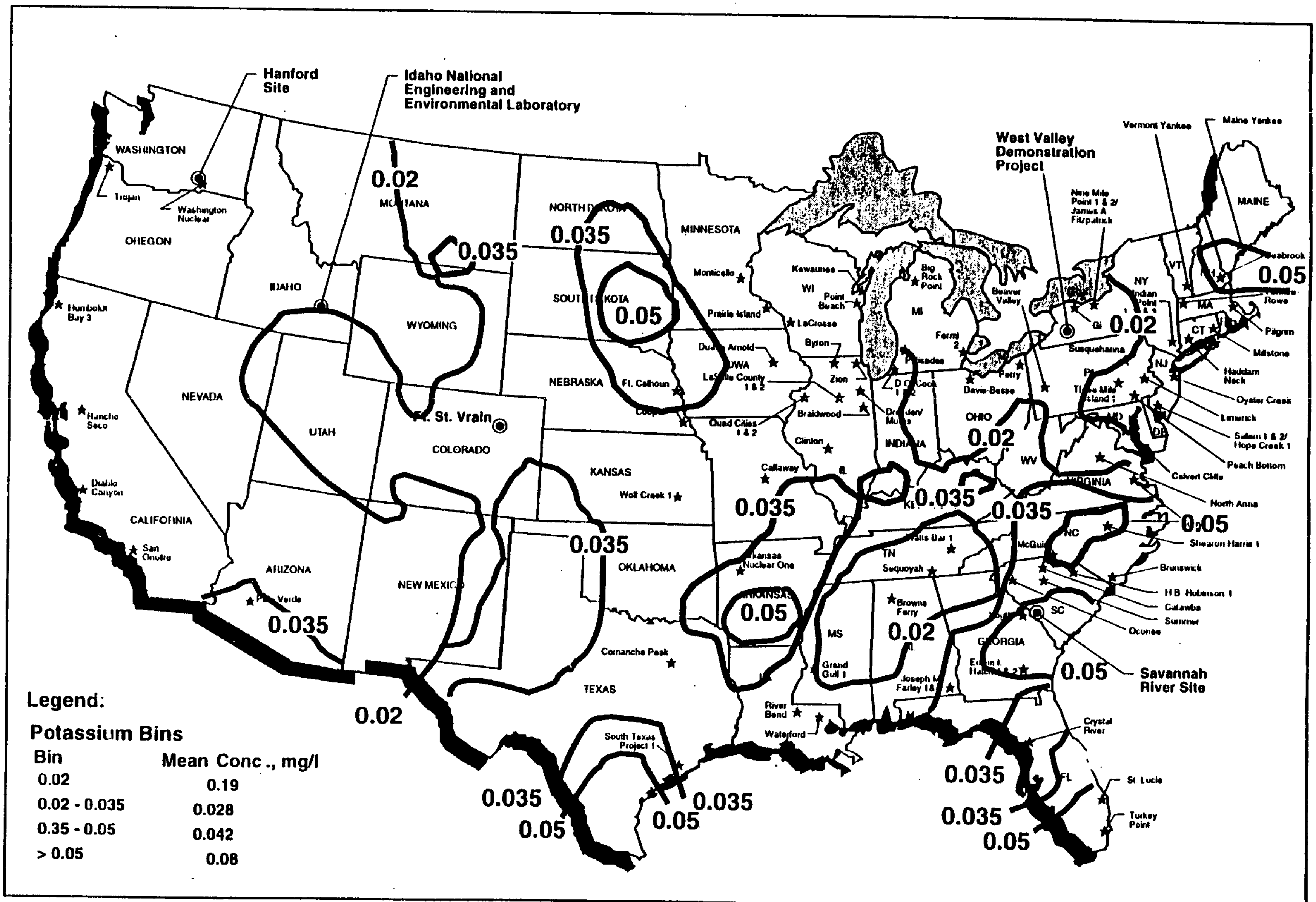


Figure 4-8. Potassium Ion Concentration Isopleths.

Table 5-1. National temperature and relative humidity data.

Site	Site location near-by city	State	Relative humidity 6 hrs/month RH>85%	Percent of year	Average temp for year, °F
Browns Ferry	Huntsville	AL	9	18.8	60.3
Farley	Montgomery	AL	16	33.3	64.9
Arkansas Nuclear One	Little Rock	AR	5	10.4	60.6
Palo Verde	Phoenix	AZ	0	0.0	72.6
Diablo Canyon	Santa Maria	CA	17	35.4	57.3
Humboldt Bay	Eureka	CA	6	12.5	52.7
Rancho Seco	Sacramento	CA	6	12.5	60.6
San Onofre	San Diego	CA	0	0.0	64.2
Fort St Vrain	Fort Collins	CO	3	6.3	51.5
Haddam Neck	Bridgeport	CT	0	0.0	51.7
Millstone	Bridgeport	CT	0	0.0	51.7
Salem/Hope Creek	Wilmington	DE	0	0.0	54.2
Crystal River	Tampa	FL	17	35.4	72.3
St. Lucie	West Palm Beach	FL	4	8.3	74.7
Turkey Point	Miami	FL	5	10.4	75.9
Hatch	Macon	GA	11	22.9	64.8
Vogtle	Augusta	GA	14	29.2	63.2
Duane Arnold	Des Moines	IA	2	4.2	49.9
Idaho National Engr Laboratory	Idaho Falls	ID	0	0.0	50.3
Braidwood	Peoria	IL	4	8.3	50.7
Byron	Rockford	IL	6	12.5	47.7
Clinton	Springfield	IL	3	6.3	50.7
Dresden/Morris	Peoria	IL	4	8.3	50.7
La Salle County	Peoria	IL	4	8.3	50.7
Quad Cities	Moline	IL	3	6.3	49.6
Zion	Chicago	IL	2	4.2	46.1
Wolf Creek	Wichita	KS	0	0.0	56.2
River Bend	Baton Rouge	LA	16	33.3	67.7
Waterford	New Orleans	LA	16	33.3	68.1
Pilgrim	Boston	MA	0	0.0	51.3
Seabrook	Portland	MA	6	12.5	45.4
Calvert Cliffs	Baltimore	MD	0	0.0	58.0
Maine Yankee	Portland	ME	6	12.5	45.4
Big Rock Point	Alpena	MI	4	8.3	47.1
Cook	South Bend, Indiana	MI	2	4.2	49.5
Enrico Fermi	Detroit	MI	2	4.2	48.7
Palisades	Grand Rapids	MI	3.5	7.3	49.5
Monticello	Saint Cloud	MN	4	8.3	41.5
Prairie Island	Minneapolis	MN	1	2.1	44.9
Callaway	Columbia	MO	5.5	11.5	53.9
Grand Gulf	Vicksburg	MS	19	39.6	64.2
Brunswick	Wilmington	NC	13	27.1	63.4
Brunswick	Wilmington	NC	13	27.1	63.4
Catawba	Charlotte	NC	4	8.3	60.1
Harris	Raleigh	NC	10	20.8	59.3

Table 5-1. (Continued).

Site	Site location near-by city	State	Relative humidity: 6 hrs/month RH>85%	Relative humidity: Percent of year	Average temp for year, °F
McGuire	Charlotte	NC	4	8.3	60.1
Cooper	Omaha	NE	2	4.2	50.7
Fort Calhoun	Omaha	NE	2	4.2	50.7
Oyster Creek	Atlantic City	NJ	8	16.7	53.0
Fitzpatrick/Nine Mile Point	Syracuse	NY	4	8.3	47.4
Ginna	Rochester	NY	5	10.4	47.6
Indian Point	New York	NY	0	0.0	54.6
Yankee-Rowe	Albany	NY	5	10.4	47.4
West Valley Demo Project	Buffalo	NY	5	10.4	54.6
Davis-Besse	Toledo	OH	1.5	3.1	48.5
Perry	Cleveland	OH	1	2.1	49.6
Trojan	Portland	OR	10	20.8	53.7
Beaver Valley	Pittsburgh	PA	2	4.2	50.3
Limerick	Philadelphia	PA	1.5	3.1	54.3
Peach Bottom	Philadelphia	PA	0	0.0	54.3
Susquehanna	Wilks Barr	PA	2	4.2	49.1
Three Mile Island	Middletown	PA	0	0.0	52.9
Oconee	Greenville	SC	7	14.6	60.0
Robinson	Columbia	SC	12	25.0	60.1
Summer	Spartanburg	SC	12	25.0	63.4
Savannah River Site	Augusta, GA	SC	14	29.2	63.2
Sequoyah	Chattanooga	TN	13	27.1	59.3
Watts Bar	Chattanooga	TN	13	27.1	59.3
Comanche Peak	Dallas	TX	2	4.2	65.4
South Texas	Victoria	TX	19	39.6	69.9
North Anna	Richmond	VA	9	18.8	57.7
Surry	Norfolk	VA	1	2.1	59.2
Vermont Yankee	Albany, NY	VT	5	10.4	47.4
Washington Nuclear	Richland (Hanford)	WA	0	0.0	53.3
Hanford	Richland (Hanford)	WA	0	0.0	53.3
Kewaunee	Milwaukee	WI	2	4.2	46.1
Lacrosse	La Crosse	WI	6	12.5	46.2
Point Beach	Milwaukee	WI	2	4.2	46.1

6.0 Temperature

6.1 Annual Average Temperature

The 30-year average annual ambient air temperature was determined from the climatological data (Reference 3) for each site and is displayed in the last column of Table 5-1.

6.2 Thermal Analysis of Surface Storage of Commercial SNF

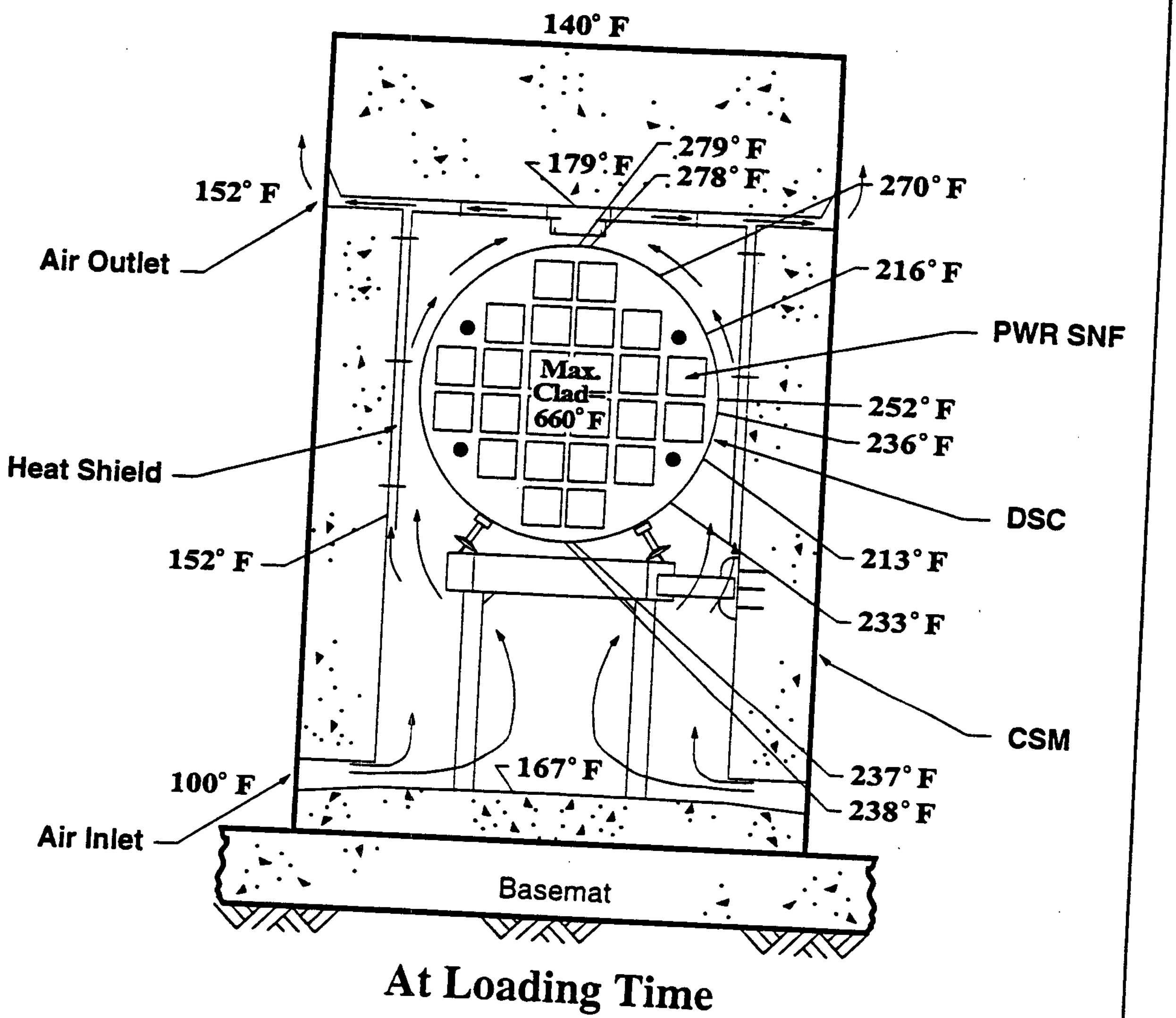
A thermal analysis was performed on a loaded surface storage unit which contained 24 PWR fuel assemblies irradiated to 40,000 MWD/MTHW and loaded at 0.66 kW/per assembly into a dry storage canister (DSC) (Reference 11). This thermal analysis was needed to guide the degradation analysis and answer a number of questions that were being raised.

A thermal analysis was performed to develop the expected temperatures that the SNF cladding and stainless steel DSC would experience during long-term degradation. The analysis included both the decay heat and the ambient temperature expected during storage. The calculations were based on information from Reference 11 and summarized on Figure 6-1. The results of this analysis can be seen on Figure 6-2a. On that figure the top curve is the calculated SNF cladding temperature and assumes that this is the average summer temperatures based on average temperatures of 80°F for Augusta, GA. The other three curves are the expected average summer, average yearly temperature, and the average winter temperatures. These average values are marked on the right margin of the figures.

The two discontinuities (the first at 150 years and the second at 260 years) reflect the loss of natural circulation cooling by vent pluggage at 150 years and roof collapse at 260 years as defined in Reference 2. The curves suggested that the heat from decay of the radionuclides in the SNF has a larger influence on temperatures than do the environmental conditions or the damage.

This initial analysis was useful in the degradation analysis so it was expanded to include ten more locations to span the conditions that are expected for continued storage. Storage locations ranged from the coldest reactor sites which included Monticello near Saint Cloud, MN; Yankee-Rowe near Albany, NY; Ginna near Rochester, NY; and Susquehanna near Scranton, PA. Average winter temperatures at these four sites are 13, 24.2, 26.1, and 27.8 degrees F, respectively. The hottest sites included Palo Verde near Phoenix, AZ; South Texas near Victoria, TX; and Turkey Point near Miami, FL. Maximum summer temperatures for these sites are 90.6, 83.6, and 82.4 degrees F., respectively. Two intermediate low temperature sites (Perry near Cleveland, OH; and Braidwood near Peoria, OH) were also selected. Rounding out the eleven sites are two intermediate sites (Vogtle near Augusta, GA; and San Onofre near San Diego, CA). Thermal analysis of storage assumed the DSC contained PWR fuel assemblies (Reference 12). Results are shown in Figures 6-2a through 6-2k.

The analysis was repeated assuming the DSC was loaded with 52 BWR assemblies. The results of thermal analysis for these BWR assemblies (Reference 12) is presented in Figure 6-3a through 6-3k.



Note: Assumes 24 PWR at 40,000 MWD/MTV loaded at 0.66 with assembly

YUCCA MTN EIS/Pubsonly/Grfx/Nat Weather SNF & HLW/6-1 Thermal Analy PWR Fuel.AI

Figure 6-1. Temperature profile for surface storage for 100° Ambient Temperature.

Commercial SNF Temperatures at Votgle (PWR)
near Augusta, GA

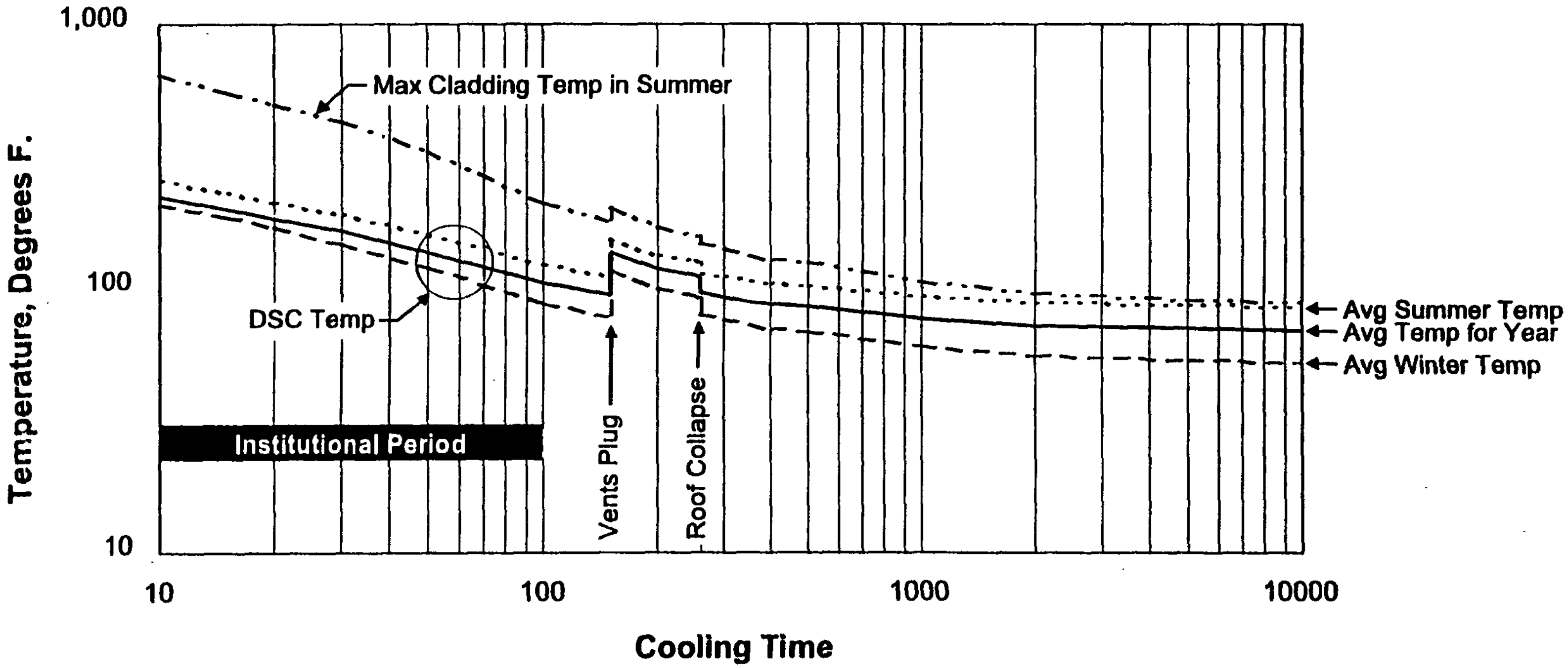


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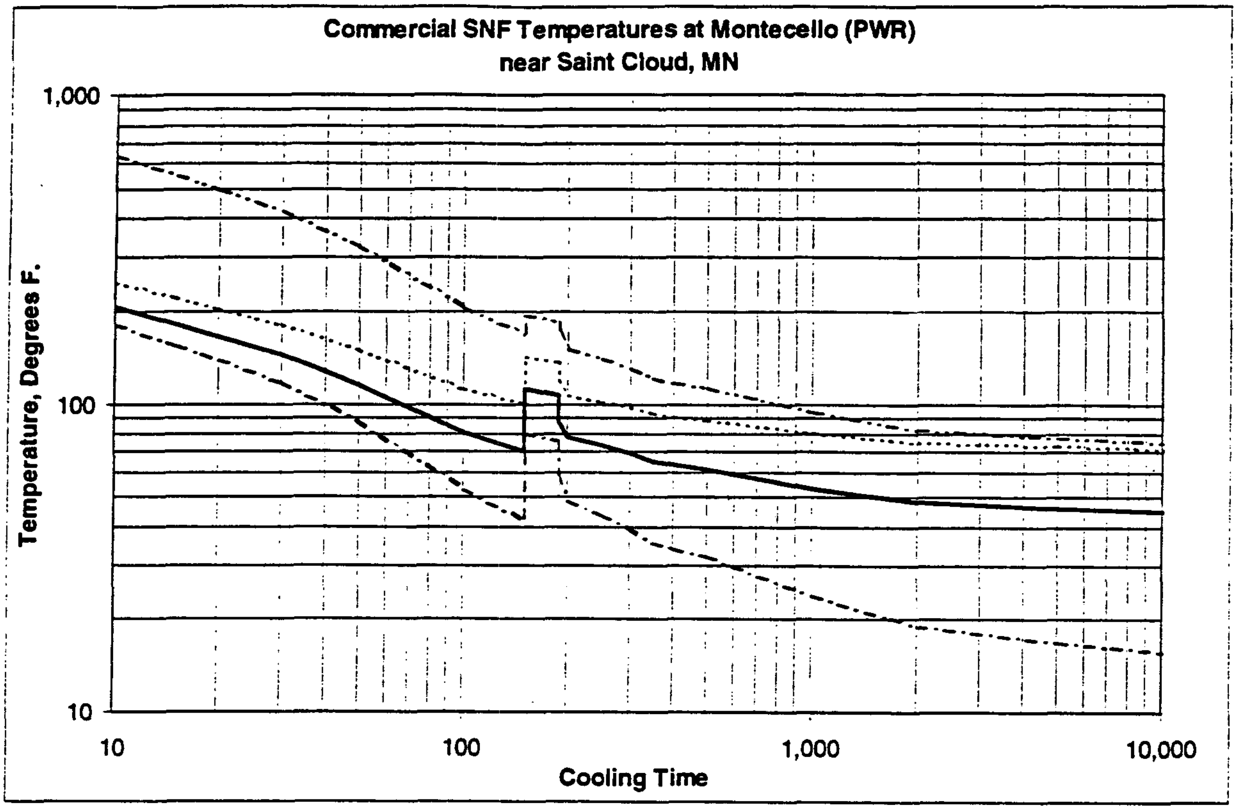
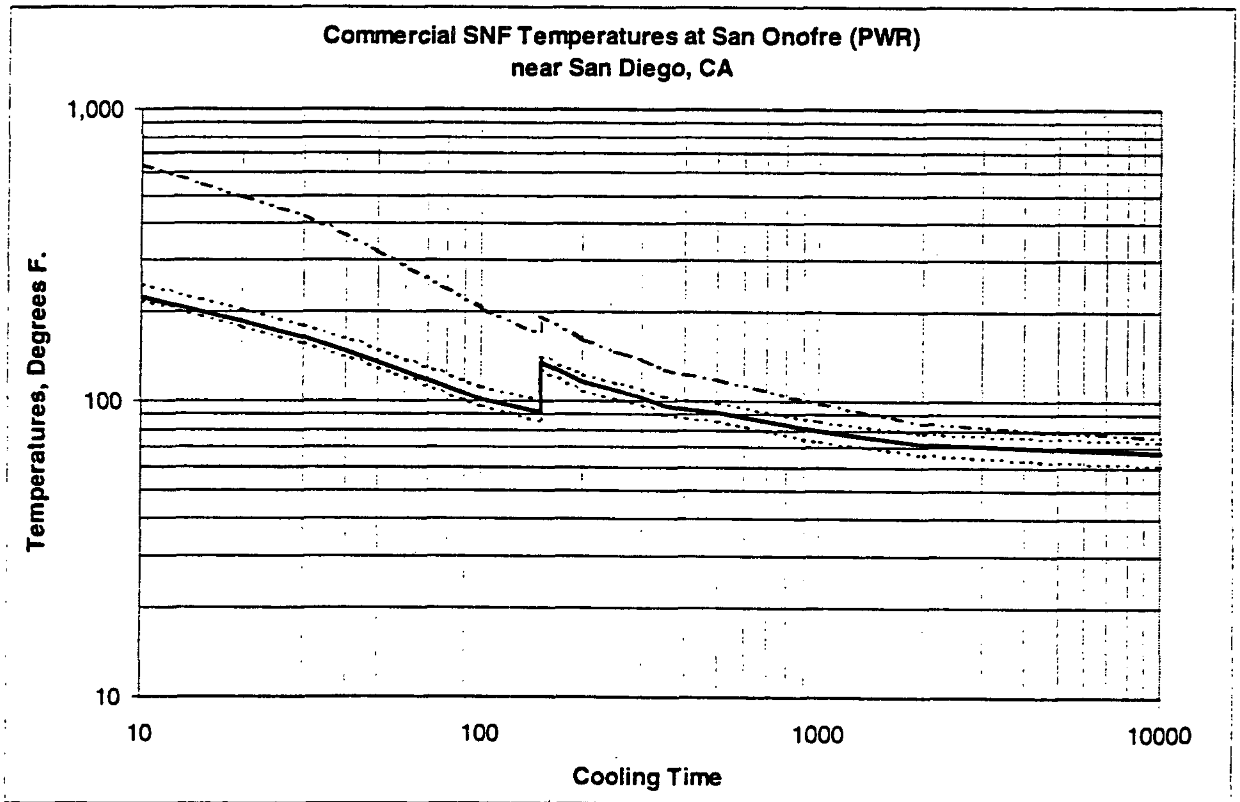
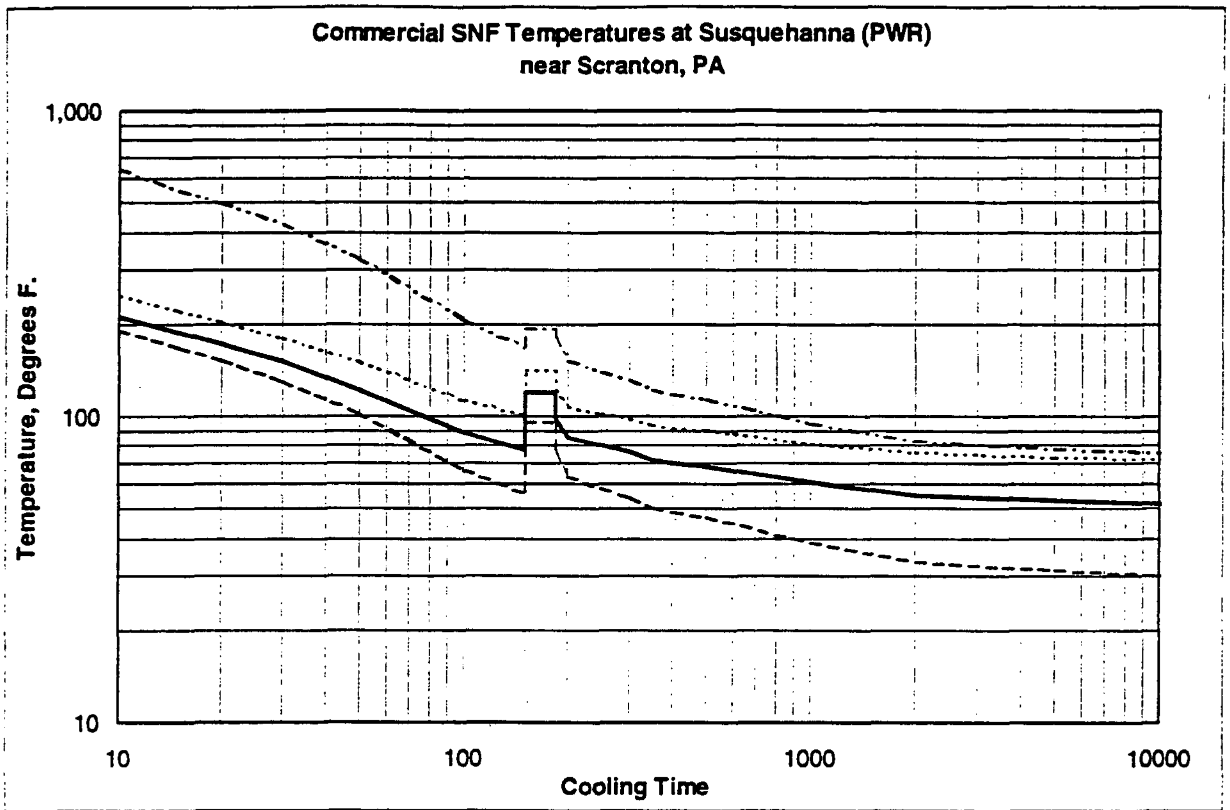
Figure 6-2a. Thermal Analysis for PWR Fuel.

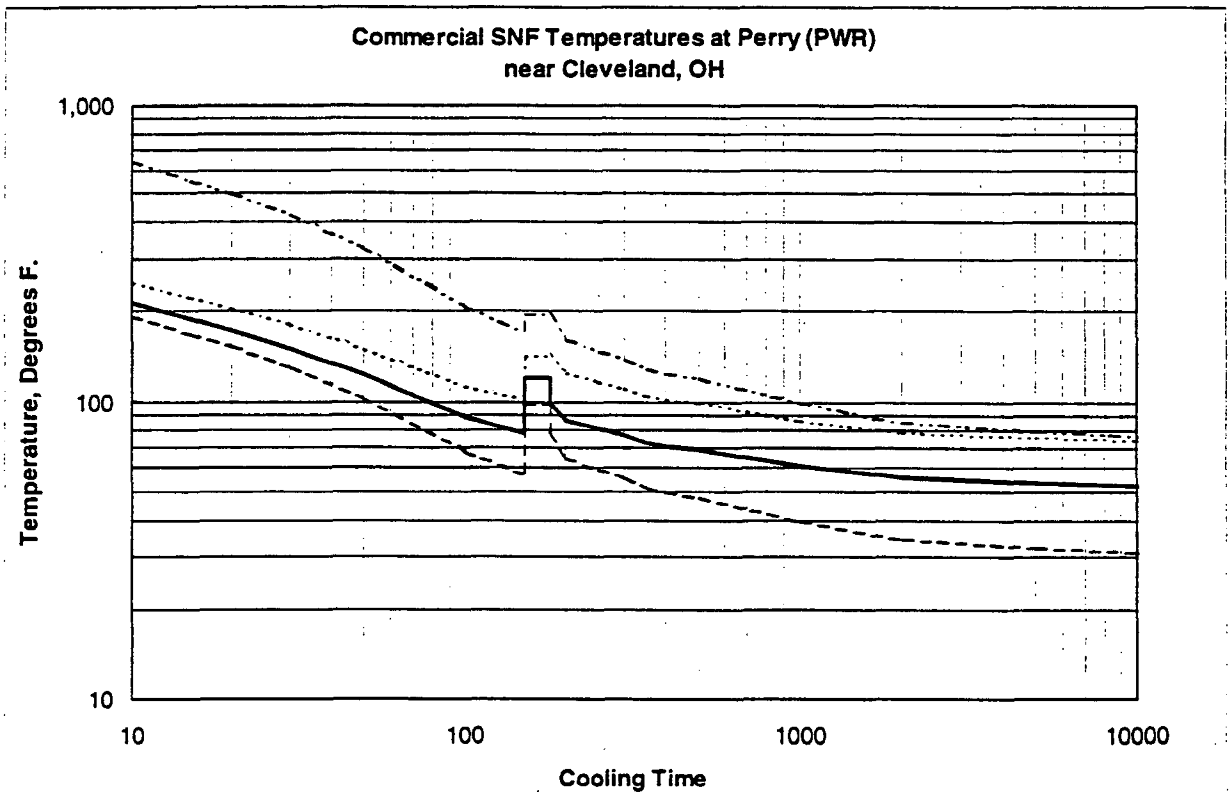
EIS Related Information



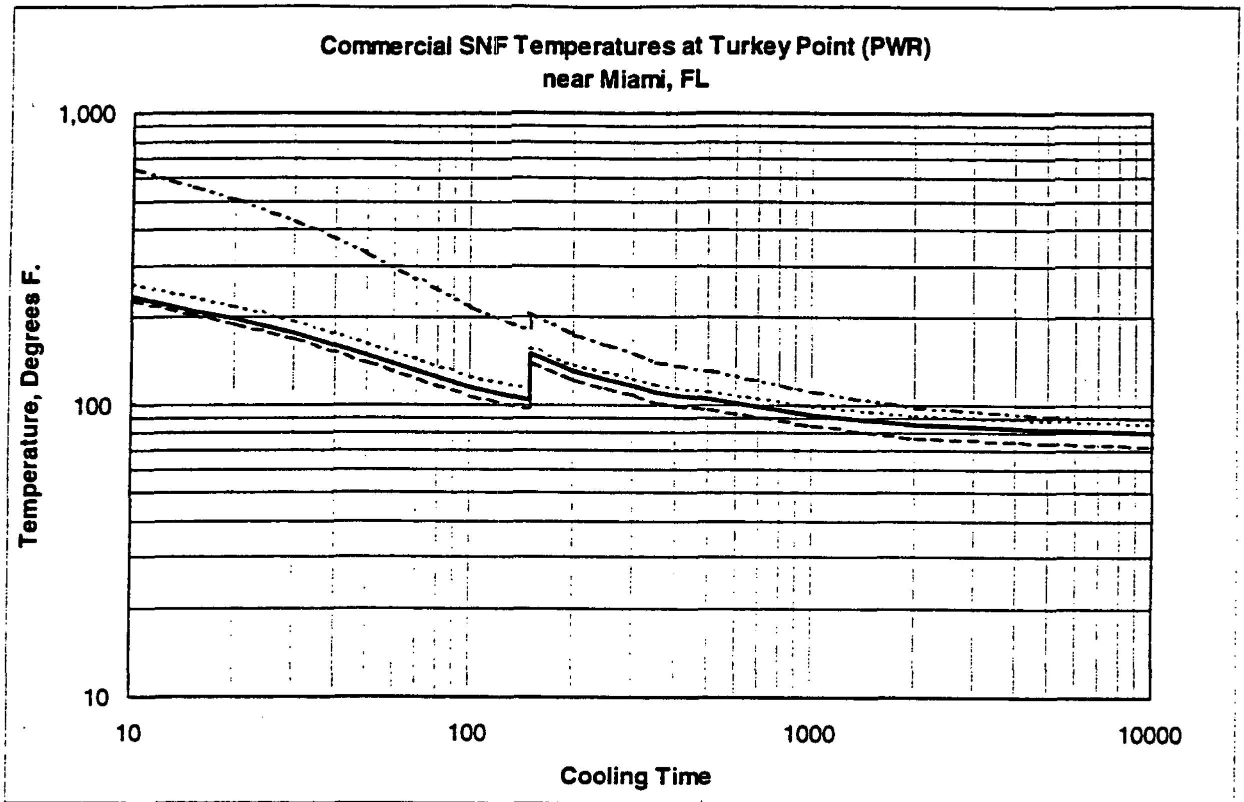


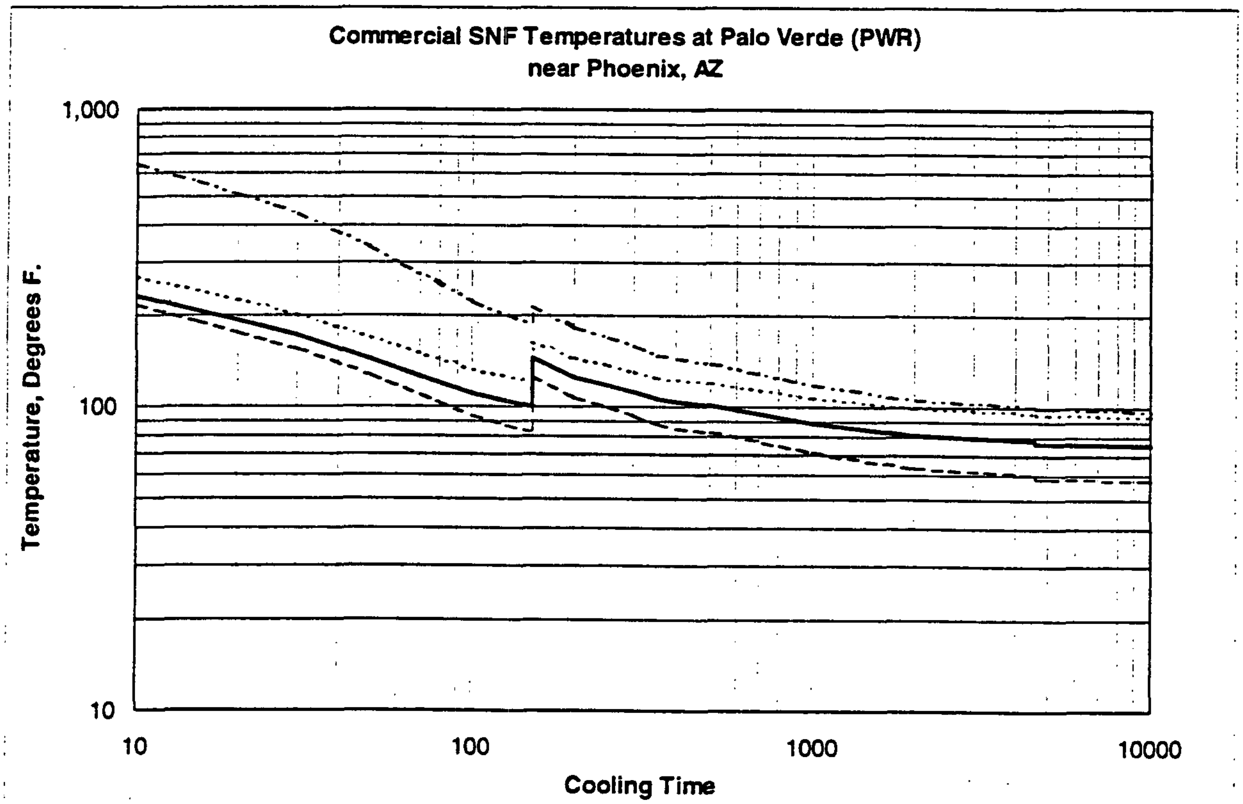
Figures 6-2b and c. Thermal analysis for PWR fuel.



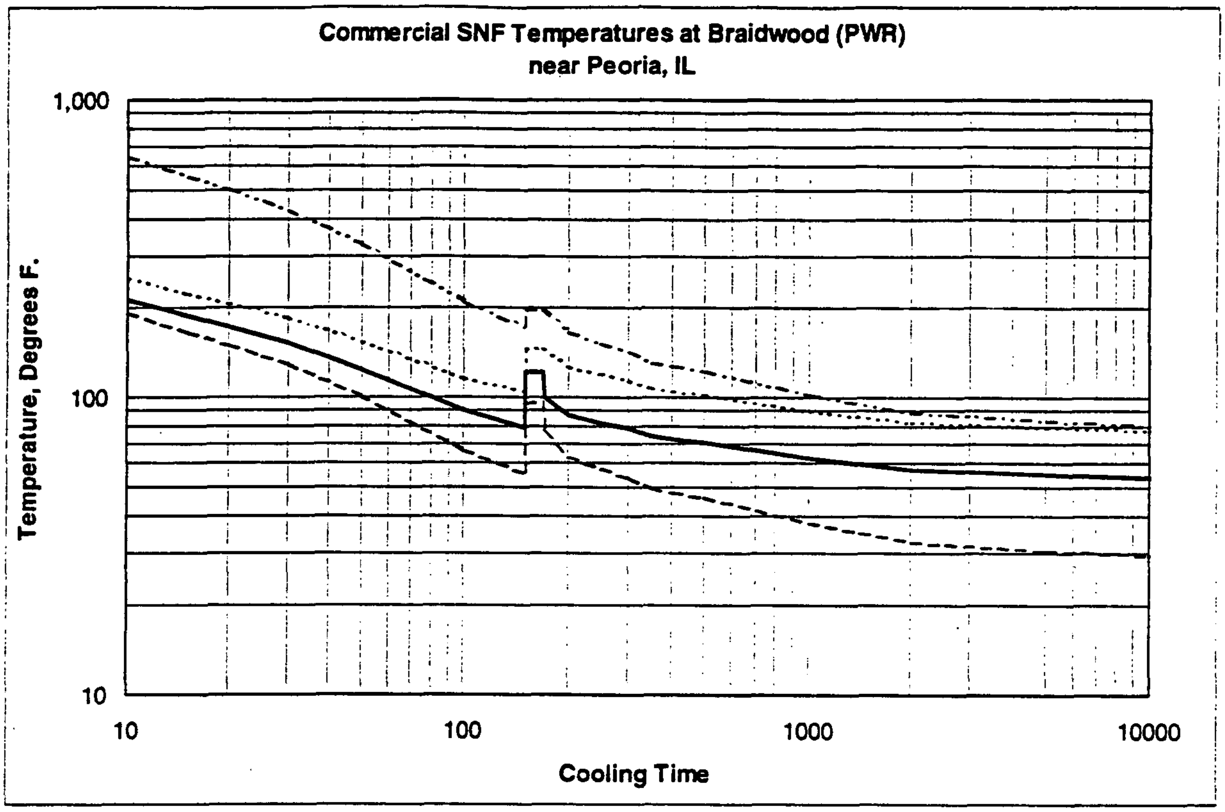


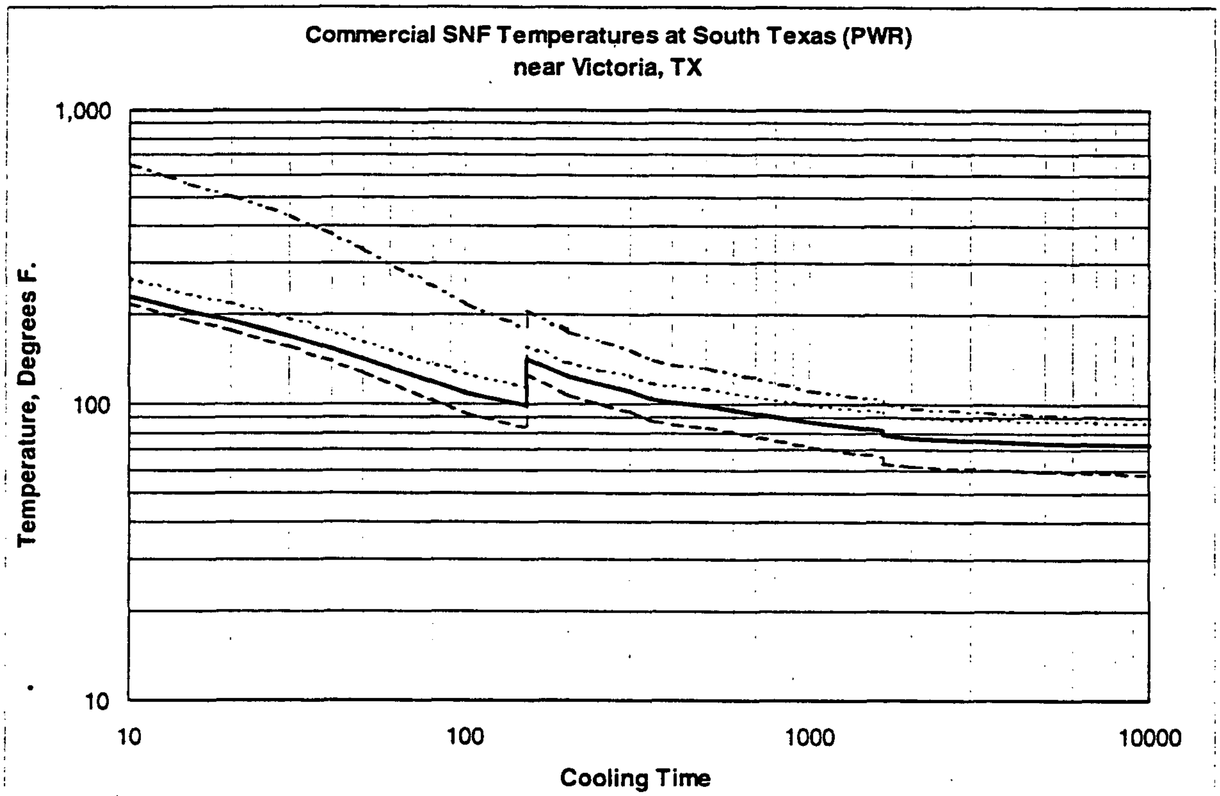
Figures 6-2d and e. Thermal analysis for PWR fuel.



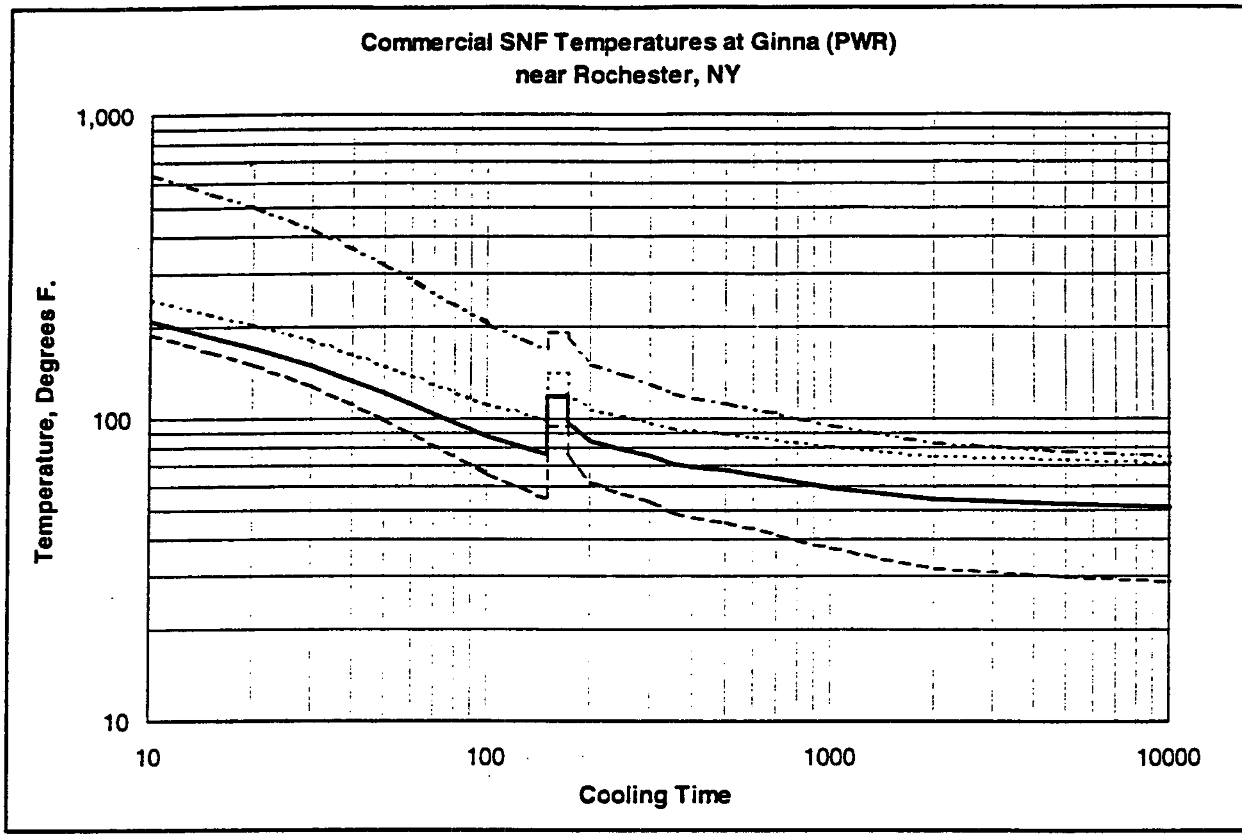


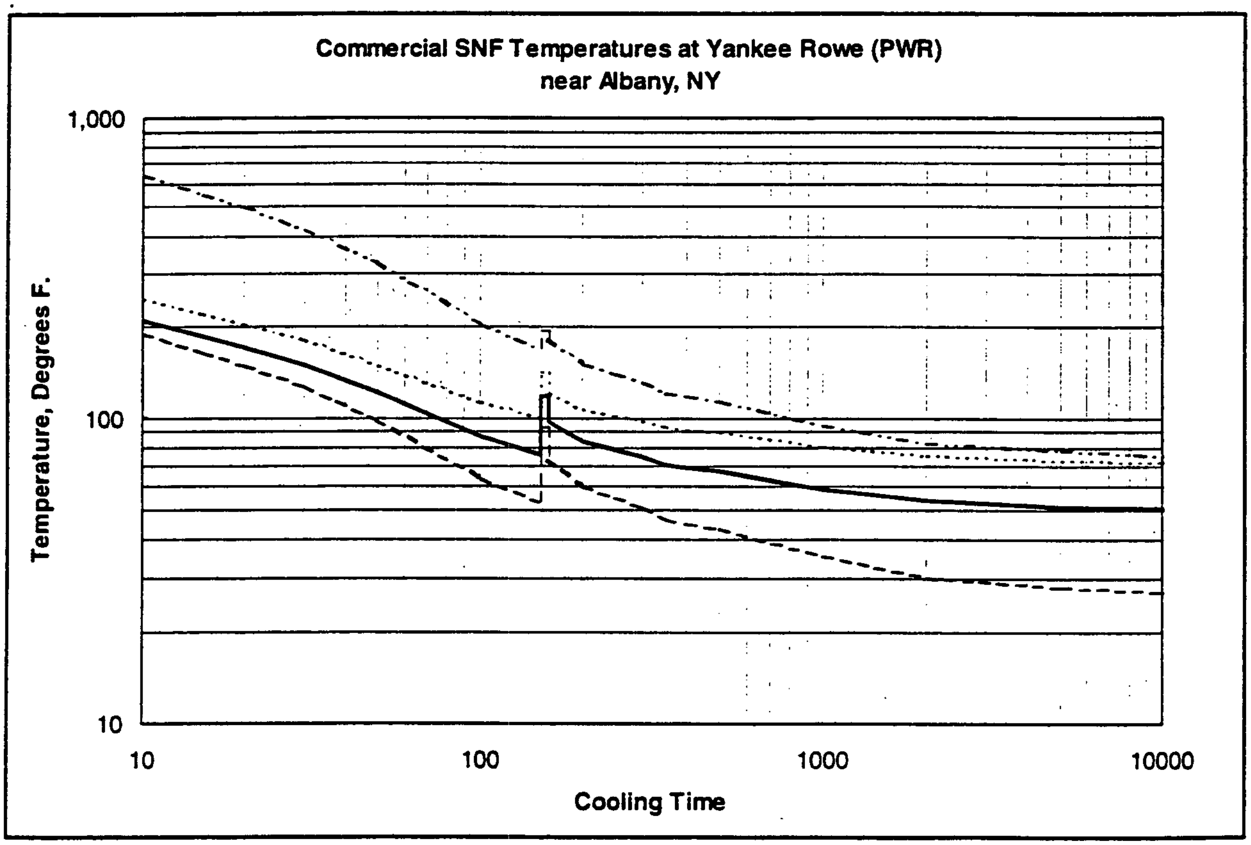
Figures 6-2f and g. Thermal analysis for PWR fuel.



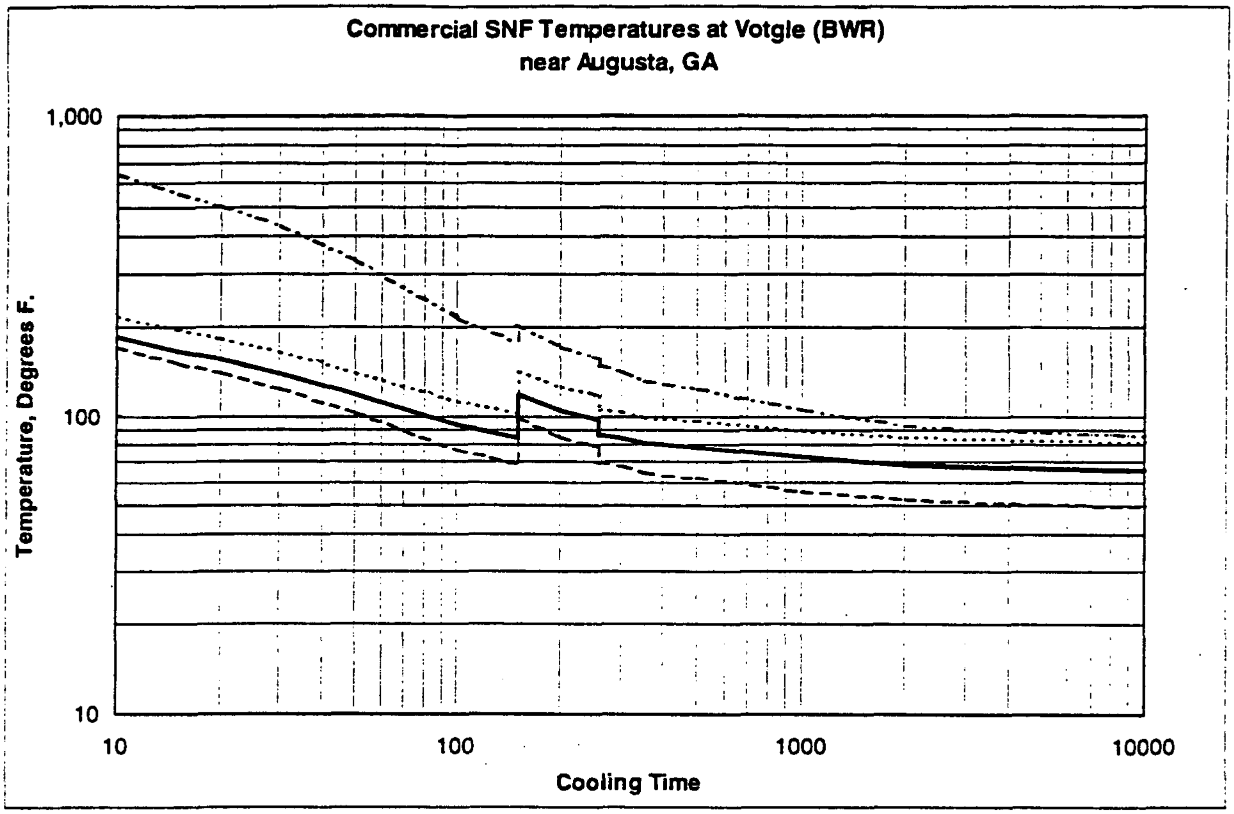


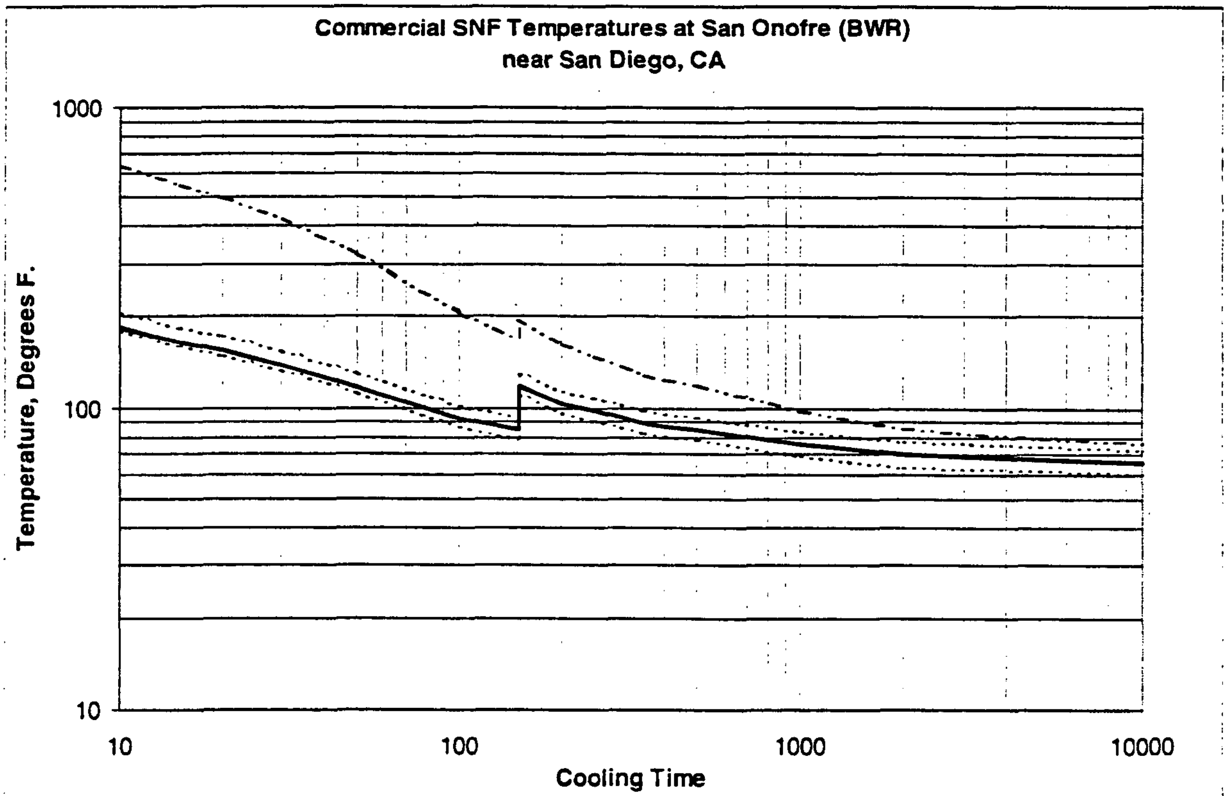
Figures 6-2h and i. Thermal analysis for PWR fuel.



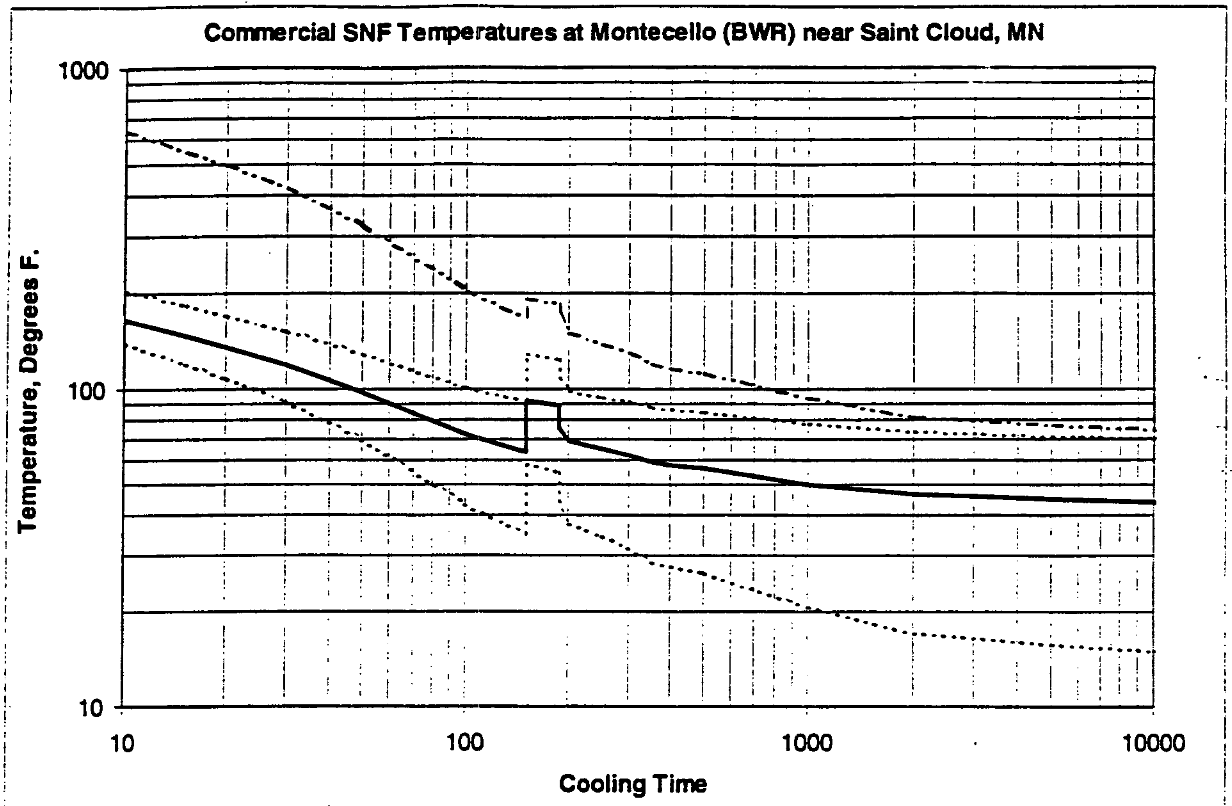


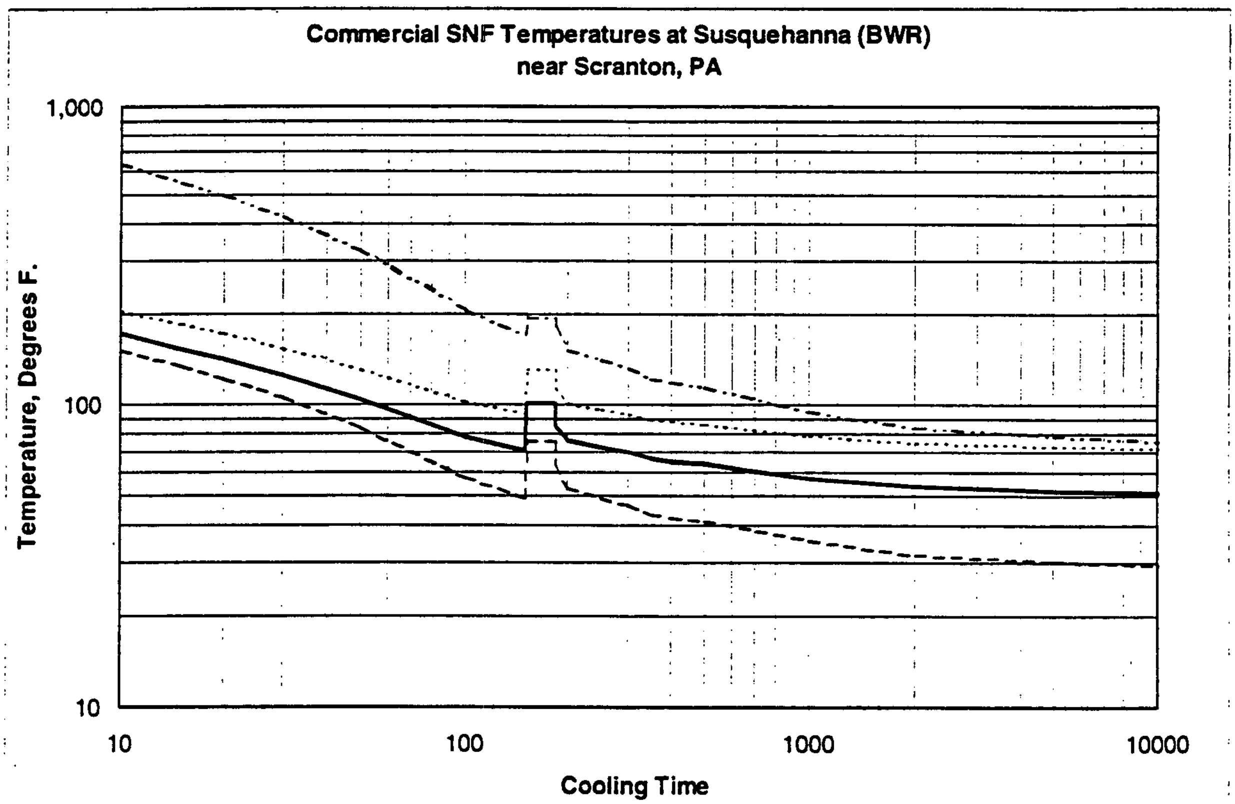
Figures 6-2j and k. Thermal analysis for PWR fuel



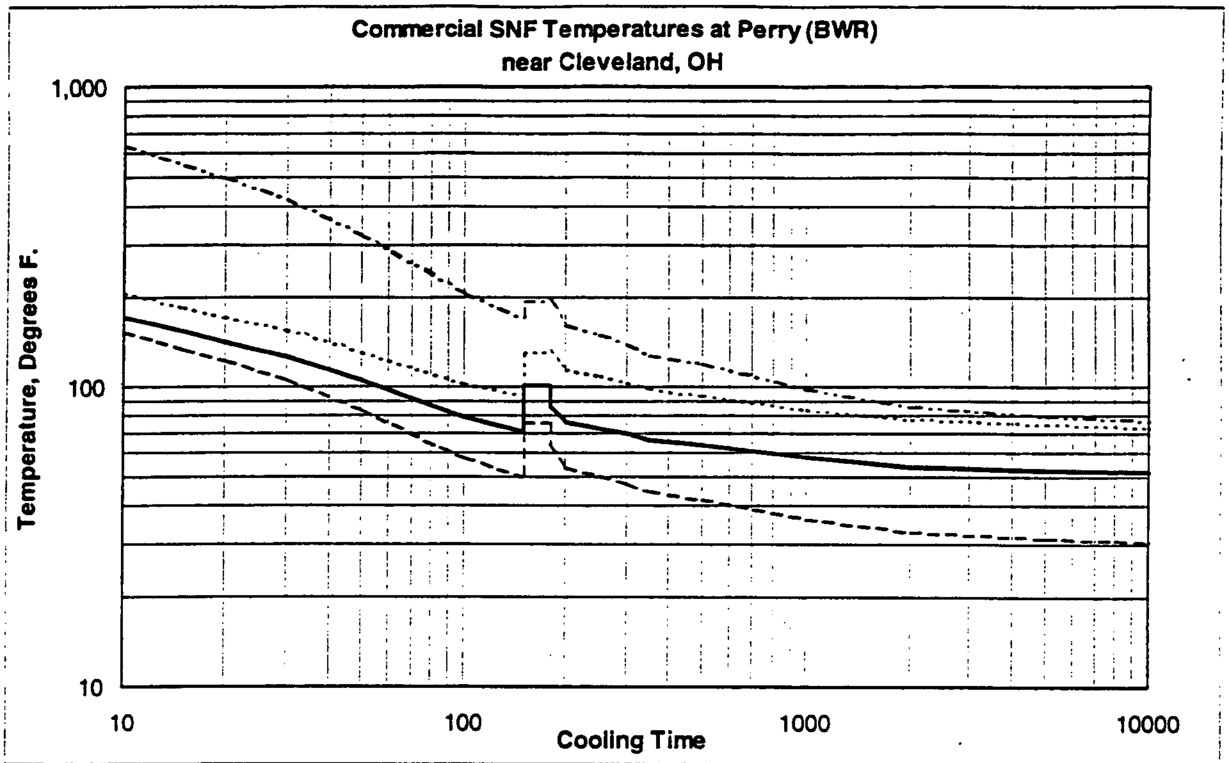


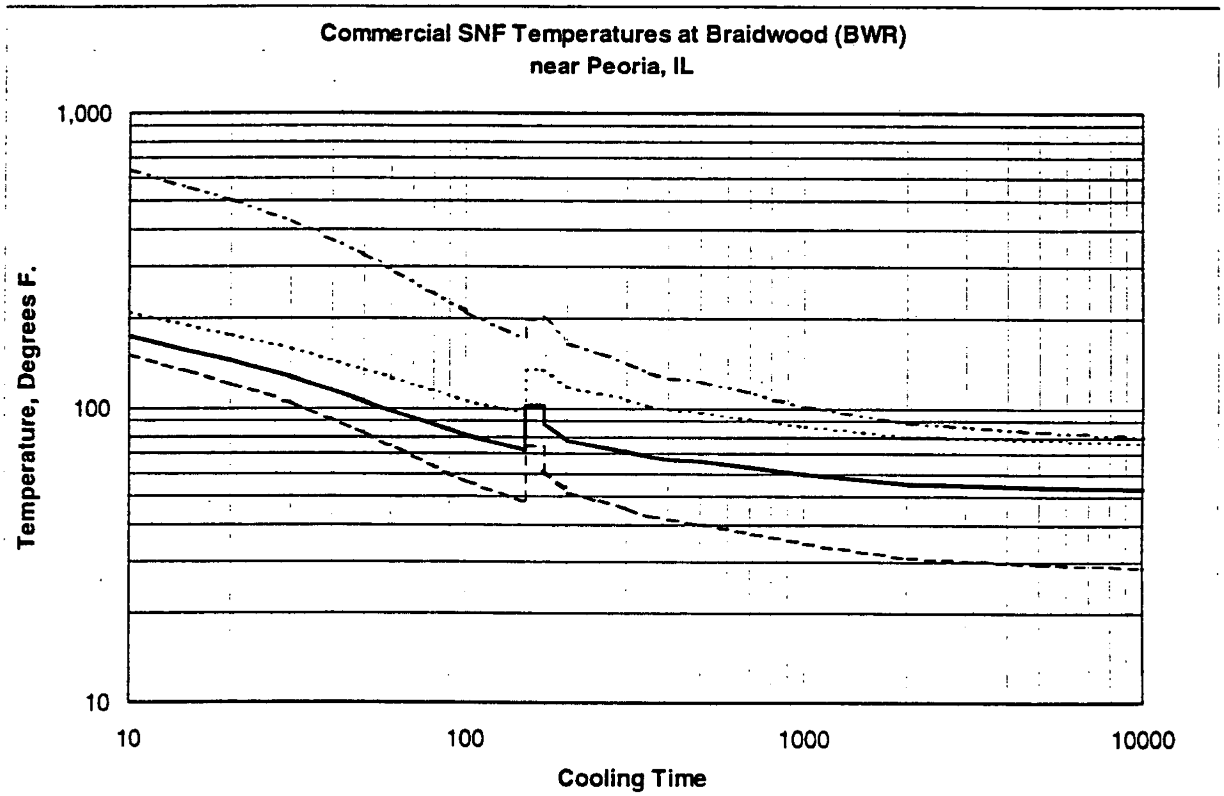
Figures 6-3a and b. Thermal analysis for BWR fuel.



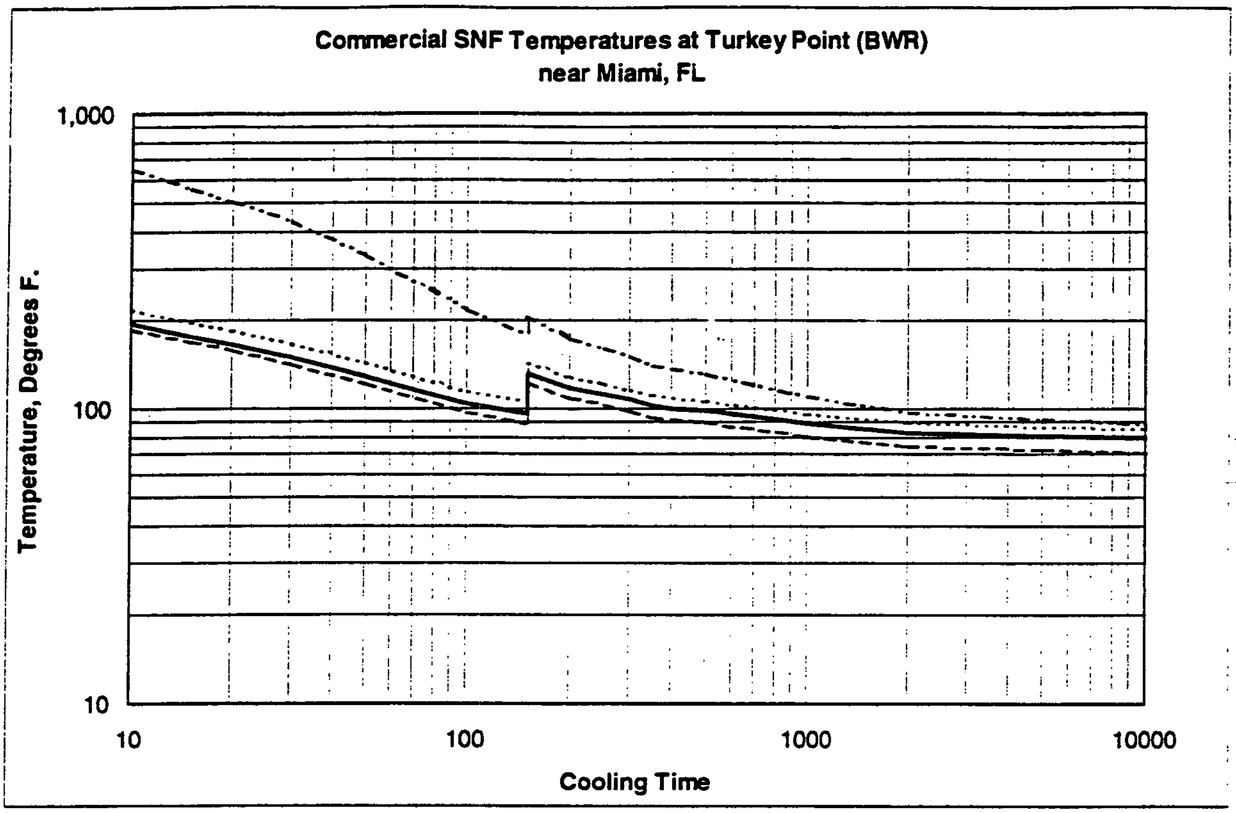


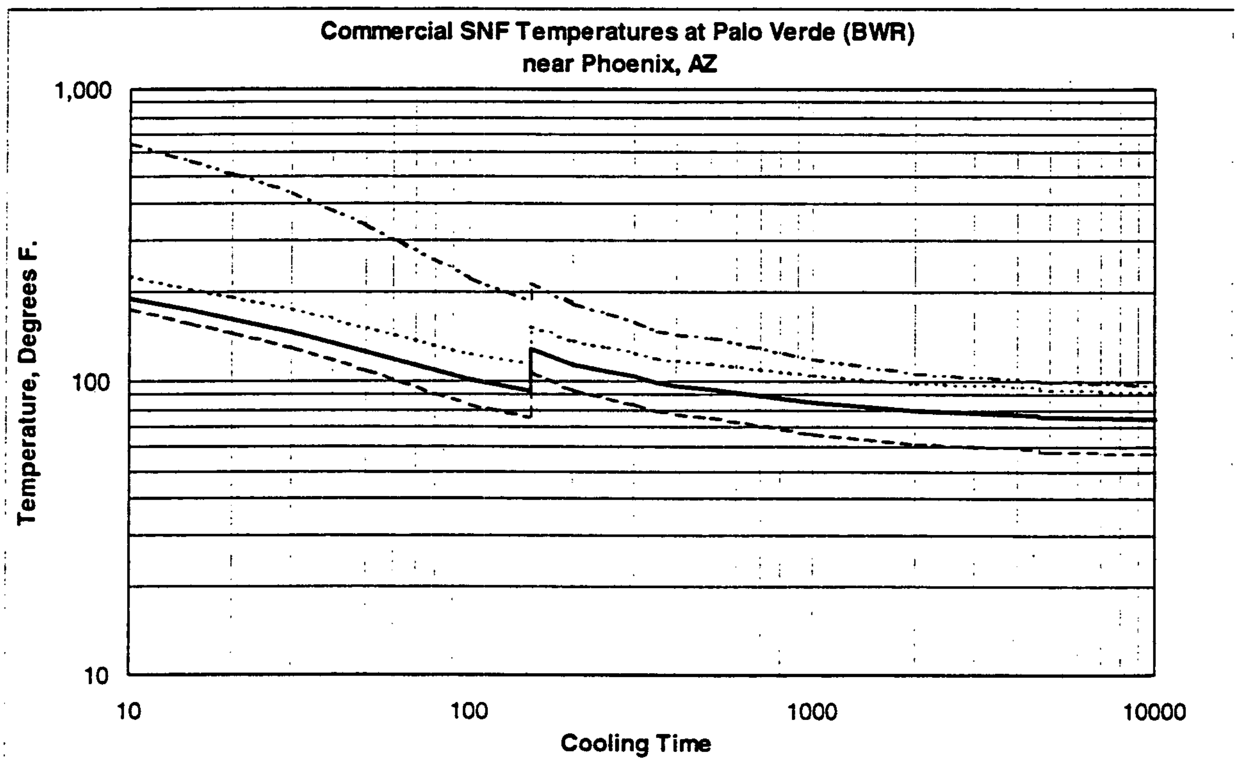
Figures 6-3c and d. Thermal analysis for BWR fuel.



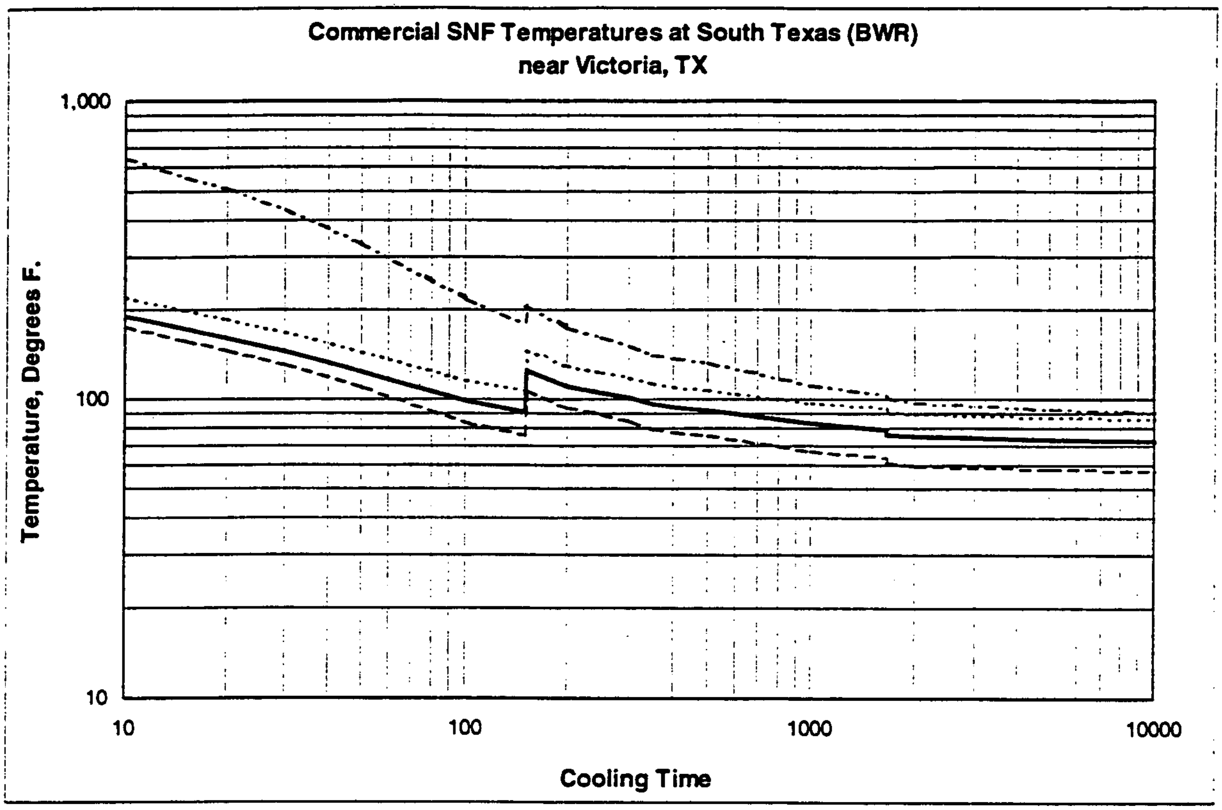


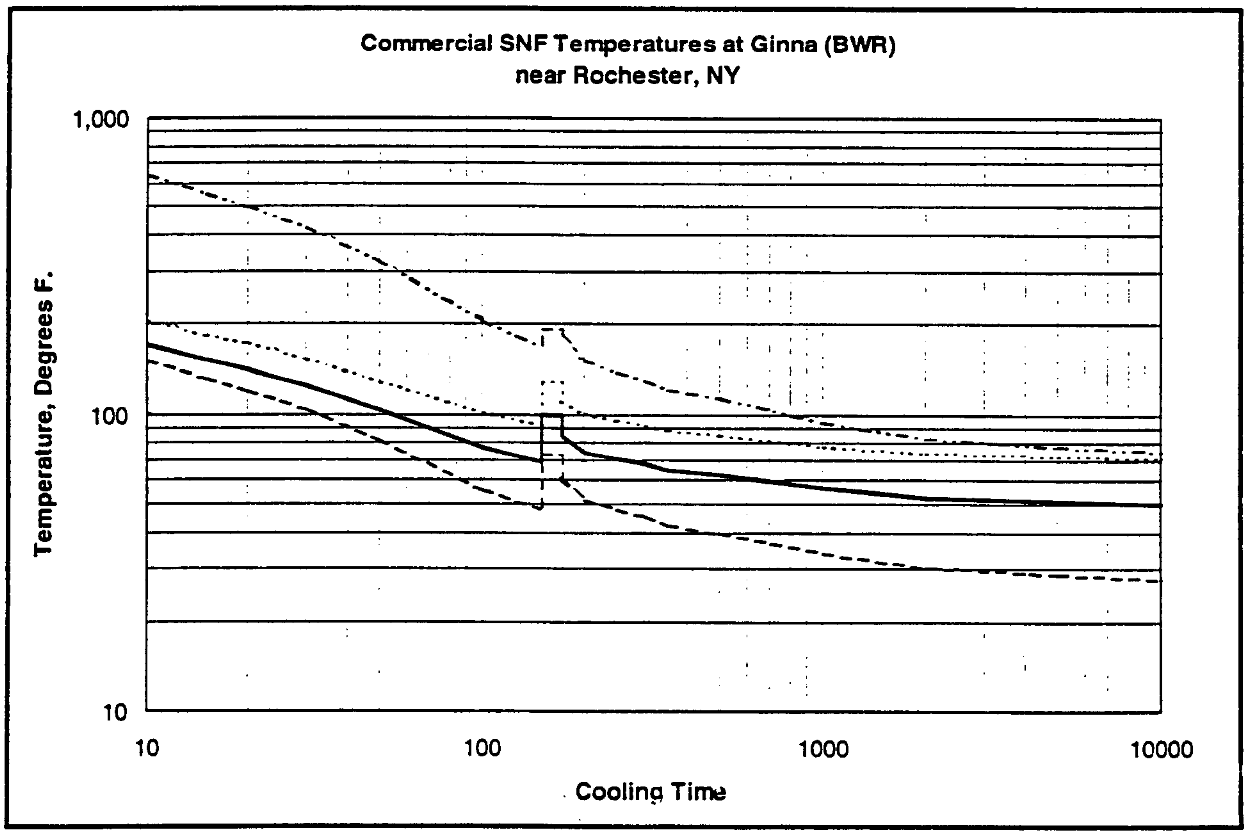
Figures 6-3e and f. Thermal analysis for BWR fuel.





Figures 6-3g and h. Thermal analysis for BWR fuel.





Figures 6-3i and j. Thermal analysis for BWR fuel.

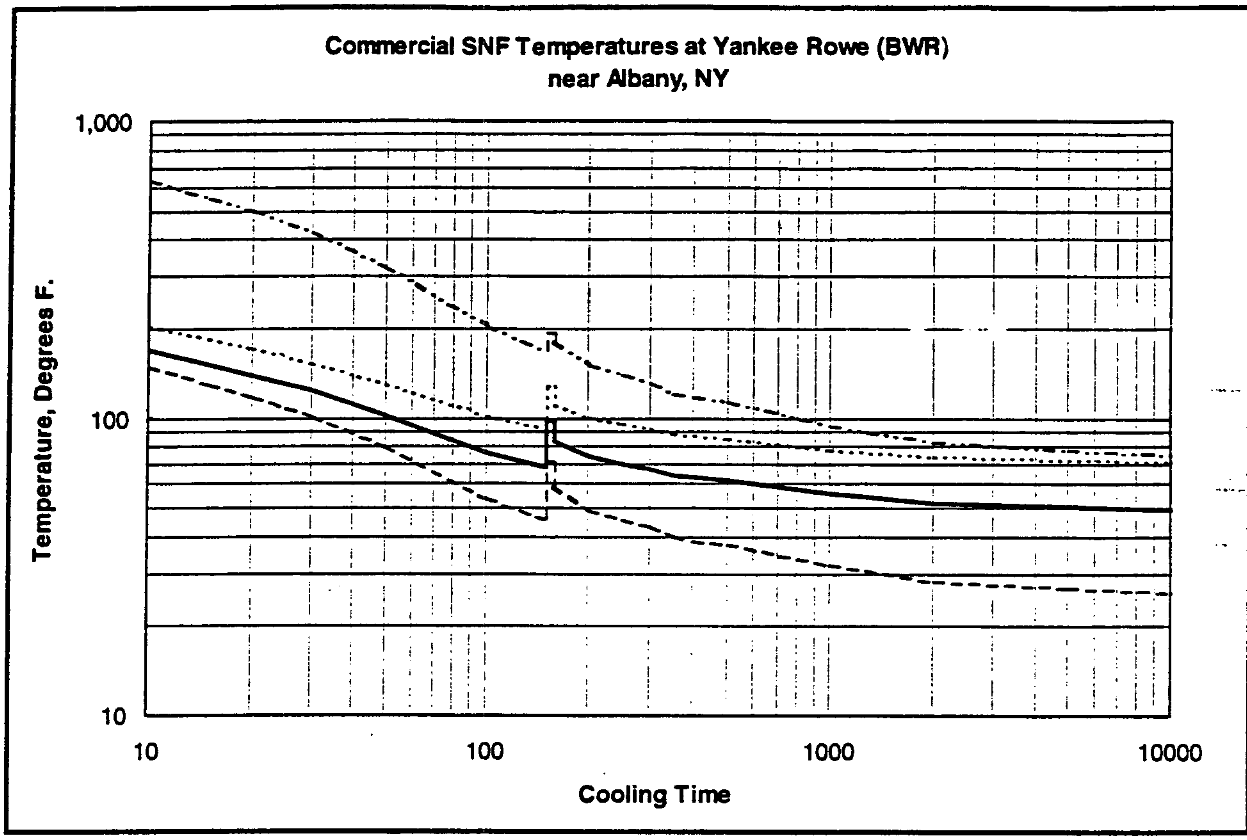


Figure 6-3k. Thermal analysis for BWR fuel.

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Reference 4. "Integrated Approach to Modeling Long-Term Durability of Concrete Engineered Barriers in LLRW Disposal Facility," Lee, J.H. et al.

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For Chloride use CL
Sulfate use SO4
Potassium use K
Magnesium use MG
Ammonia use NH4
Nitrate use NO3
Calcium use CA
PH use LABH

Reference 9. "Analytical Approach for Estimating Releases of Spent Nuclear Fuel and High-Level Waste for the Yucca Mountain Environmental Impact Statement No-Action Alternative," Battelle Pacific Northwest Division, Richland, Washington.

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